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THE PLANETS: SOLVED AND UNSOLVED PROBLEMS

by D. Ya. Martynov

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D. Ya. Martynov

ABSTRACT. A survey of the resolved and unresolved problems of planetary physics is presented. The contribution of worldwide research in the fields of astronomy, surface astronomy, space technology and other fields to planetary physics is reviewed. A list of physical constants for all planets and their satellites is given.

1. INTRODUCTION

Since the planets of the solar system have become the topic of space /3* investigations, interest in them has grown to an extraordinary degree. Studies have begun to be made both from spacecraft flying near them and by scientific equipment in direct contact with the atmosphere or ionosphere of a planet and even with its surface.

Planetary research has undergone a development which can only be described as explosive. Only this explosion is creative rather than destructive. The size and pace of the investigations, which in the quite recent past have been purely academic, have given way to extensive experiments and to ardent, sometimes hasty discussions of the results extracted. The approaching possibility of interplanetary travel has had a mysterious, but very active effect on all these events.

*Numbers in the margin indicate pagination in the original foreign text.

Astronomers, design engineers, scientists representing related sciences, and simply inquisitive persons, are all showing interest. Correspondingly the number of scientific investigations has grown and extensive new information, based on the observations, has appeared. An avalanche of new facts has fallen upon us, some important, and some minor, some substantial and others secondary, some true and some doubtful.

Just as for a ship at sea or an airplane in the air, the most hazardous part of the voyage for an interplanetary craft is the beginning and the end. But in transit the craft is also confronted with a difficult problem, to maintain a proper course and not deviate from it. Engineers designing space rockets and interplanetary scientific stations and ballistics engineers who determine the motion of the rockets at the beginning, enroute, and at the finish, have all turned for information to astronomy. All previous accomplishments in astronomy have been mobilized to solve what is essentially an engineering problem — that is, to move a spacecraft toward a given target. Here precise knowledge is needed on the structure of the solar system and its dynamics, and a linear scale of interplanetary distances is needed in order to accurately utilize the precepts of celestial mechanics. These methods are used to determine the rocket's trajectory. The observational procedures of astronomy are also needed, as are the facts already extracted /4 concerning the physical nature of planets and interplanetary space.

All these achievements of classical astronomy were mobilized to serve the new problems created by mankind. Astronomy, this most ancient of sciences, is still the center of attention even today. Only now the requirements imposed on accuracy of the answers are immeasurably greater than before. The responsibility of astronomers has grown to include forecasting the conditions involved in the motion of spacecraft, their launching and landing. On the other hand, the landing of a space missile equipped with scientific equipment, or even its orbit near a planet, as the successful flights of the Soviet and American unmanned interplanetary stations showed, will return a huge amount of highly reliable new facts. The success of these

flights has been tremendous. It has generated the idea that the surface study of planets is henceforth a thing of the past, and must give way completely to space technology methods.

A tragic delusion! Considerable time must yet pass before even the nearest planets can be studied exclusively with spacecraft, and the more distant ones will be studied for many years to come by surface methods that only will be developed and refined along with the space technology methods. It is these experiments, that is, those on the surface of the Earth, that will, to a significant degree, determine the topics of space experiments involved in studying the planets.

The situation has not changed even following the latest success in astronautics, that is, the landing on the Moon by the crew of "Apollo-11" and its return to Earth carrying rock samples from the lunar surface, miles of photographic film and results of observations carried out on the surface of the Moon for a period of two hours, while the instruments which they left on the Moon have continued to carry out the experiments set up there. The crew of the "Apollo-11" brought to Earth new information which is distinguished by its high degree of reliability, but how little this is in comparison with the knowledge we must have about the entire Moon and all of its geographic (or more precisely, its "selenographic") and physical properties! This will all be possible only after trips to the Moon have become regular scheduled flights.

Then does planetary research involve only the concept of interplanetary travel? The answer to this question can only be a negative one. The primary, and even ultimate, goal of any natural science is that of solving the origin and development of the topics and phenomena to be studied. And astronomy, as a subdivision of planetary research, has the fundamental problem of explaining how and when our planetary system came into being around the Sun, how it evolved, and how it will be in the future. To solve this problem, it is essential to have knowledge about the planets: in addition to the usual characteristics such as mass, size, form, and rotation period, it is necessary /5

to know the structure and chemical composition of the surface of a planet, its temperature, as well as the temperature of the atmosphere, and the qualitative and quantitative composition of the atmosphere. Attempts must be made to discover the internal structure of the planets and the relationship between planetary matter and comets, meteors and other interplanetary matter, based on the external characteristics. /6

The study of the dynamics of planetary atmospheres greatly contributes to the field of climatology, since it reveals the possibility of understanding the motions characteristic of planetary atmospheres, as well as motions unknown on Earth.

All this may be studied from the Earth's surface with great success, and, in fact, is being studied by astronomers. But space technology procedures are of invaluable assistance. However, let us not cherish the vain hope of expecting in the near future, "at last"..."from now on...", "now...", etc., that we shall know everything we wish to know about the planets, their formation, and their evolution. Being on Earth, we are developing a whole branch of science — geophysics — dedicated to the Earth itself, but we are infinitely far from being satisfied with the knowledge gained! As yet we have no widely accepted concept as to the bowels of the Earth, its chemical composition and temperature at great depths. We can not even solve beyond doubt the question as to whether the origin of petroleum is cosmic or organic, and we still often err in the forecasting of weather. The list of such unresolved problems could continue without bound.

In the present booklet we wish to give a survey of the resolved and unresolved problems in planetary physics that are of the greatest interest today. We must say that these do not always coincide. For example, the degree to which the surface layer of a planet is friable is interesting, both theoretically and practically. Theoretically, because to some degree it determines the temperature conditions of the surface layers of the planet, and practically, because the conditions for landing a spacecraft depend on it. But in the first instance the astronomer is interested in the nature of

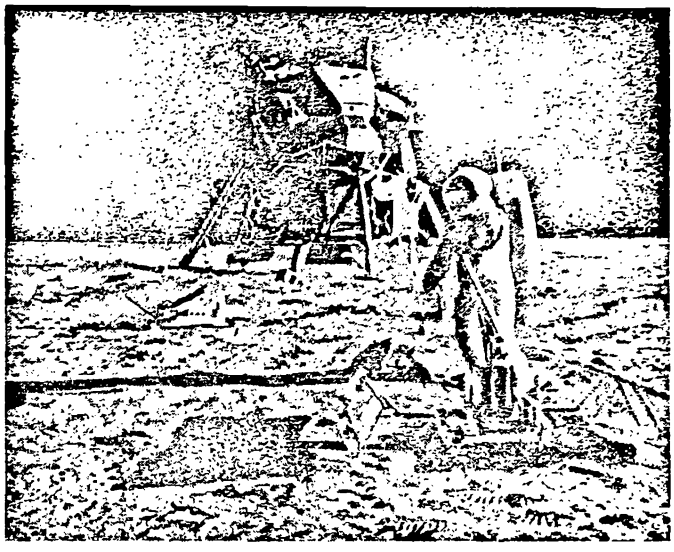

Figure 1. First men on the Moon. Expedition of the space ship "Apollo-11". Landing module "Eagle" on the Moon, July 21, 1969. Astronaut Aldrin near seismometer he set up, equipped with solar batteries. Left center shows instrument for reflecting laser beam. Rear part shows imprint of Aldrin's boots on the lunar soil.

the surface layer, its petrographic structure, thermal conductivity, etc., and in the second instance he is concerned with its capacity to withstand a dynamic and static load. The answer to the practical question of strength may be given with /7 the answer to the first — a theoretically significant question — but, unfortunately, it is far from having that degree of reliability and accuracy which the designer must have. It is not surprising that the paths of astronomical and design problems often coincide in the area of planetary research, although the means for solving them are not always identical.

In this survey, we shall not give a systematic discussion of the facts and methods employed in planetary research — this is the concern of textbooks. We shall speak about the latest successes and achievements in studying the planets, making reference to the surface methods, since space technology methods are quite widely known. And for this same reason the Moon will not be a matter of special concern, because formally the Moon is not a planet, but a satellite. The Moon is becoming an ever increasing topic of direct investigation. But any systematic investigation of the Moon by such means is a long way off!

With this booklet, the author addresses himself neither to the reader who is a specialist in astronomy, nor to the reader who is making his first

steps in planetary astronomy, but rather to the reader who has general knowledge as to the current state of the art in planetary science. The present essay may perhaps permit the reader to evaluate the degree of reliability of his knowledge and direct his attention to those fundamental problems which are still to be solved by the methods of surface astronomy.

2. PLANETARY SURFACES

Our knowledge of planetary surfaces is limited to the inner planets, or /8
planets of the Earth group as we still call them — that is, Mercury, Venus, and Mars. We can also include the Moon among them. On Jupiter, for example, all that we can see are atmospheric and cloud formations. It would appear that we might say the same with respect to Venus, since we can see only its cloud layer, which is very thick and has almost no opening. But in quite recent times, by using radar impulses, it has been possible to penetrate the atmosphere of Venus and, reflected from the solid surface, to return to Earth the first information on the various formations on the planet's surface. It has now become possible to compile the first schematic map of Venus where individual features are shown, although it is true these features have as yet not been interpreted. But the map of Mercury, compiled from visual telescopic observations (Figure 2), contains only dark formations on a light background, the nature of which is completely unknown.

Ultimately, it is the observations from a planet's surface or stable atmospheric formations that will permit the period of rotation around its axis to be determined. This period, in conjunction with the mass, dimensions, and shape of the planet, will offer the first signs of its internal structure. Along with this, the alignment of the axis of rotation is derived from such observations and it becomes possible to map the planet.

At the present time, we already have at our disposal the correct values for the periods of rotation of all the major planets including Mercury and Venus, the data for which were obtained only by using radar (see page 54 for details). The 59-day period, found for Mercury, indicates an angular velocity of rotation equal to the angular velocity of its motion around the Sun at perihelion, that is, on that orbital segment which is nearest the Sun. Tidal forces have apparently played a role in establishing such an equation.

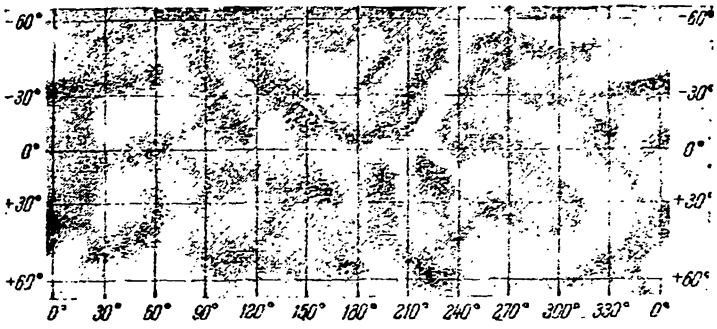

Figure 2. Map of the surface of Mercury, compiled by O. Dolfuss from observations at the observatory Pic du Midi (France).

The 243-day period of Venus' retrograde rotation is coupled with the rotation period of Venus and Earth around the Sun, such that at each minor conjunction of Venus — that is, when Venus is located between Earth and Sun — the same side of Venus /9 is turned toward Earth. The Earth occupies the same position above the horizon from some point on the surface of Venus every 146 days, and the minor conjunctions of Venus are repeated every 584 = 4 x 146 days. As to whether this alignment is random or not, we still do not know.

It is interesting that the previous visual observations of Mercury resulted in a period of rotation around its axis of 88 days, equal to the period of its rotation around the Sun. It was found that Mercury has the same side always turned toward the Sun. This conclusion is no longer valid, but all the ancient drawings of Mercury's surface which previously served for its mapping with an 88-day period, surprisingly enough, are satisfactorily encompassed by the new period of 59 days. It seems that such a situation is due to indeterminancy in the drawings, which in turn, is due to the problems involved in observing Mercury.

We have today maps of the surface of Mercury and of Mars. That of Mercury is very crude, but the map of Mars contains numerous details, the comparison of which at different oppositions indicates a substantial time-variability in the face of Mars, not only due to variations in time of year (Martian), but independently of them, as well.

Of course, the most detailed maps are those of the Moon; global maps /10 have been compiled in scales of 1:5,000,000 and 1:10,000,000. For individual

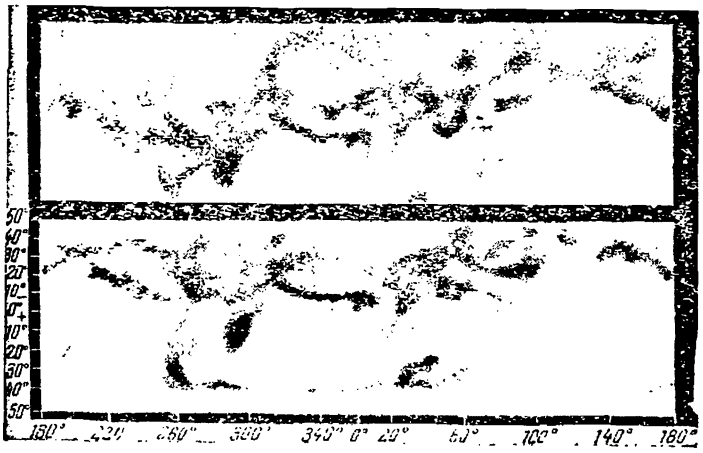

Figure 3. Map of the surface of Mars in oppositions of 1956 and 1958. South - above. In 1956 Mars had mainly its southern hemisphere turned to the Earth. On the 1958 map, the aerographic latitudes are shown on the left and the longitudes at the bottom.

regions, larger scale maps have been compiled which were produced by the flights of spacecraft around the Moon. A map of the equatorial zone has been compiled for the visible side of the Moon in a scale of 1:1,000,000. Here terrestrial and space investigations successfully work together: to compile large-scale maps with the aid of highly informative photographs taken at close distances, a large number of reference points is required, the position of which is determined on the surface of the Moon (selenographic coordinates) from ground observations, connecting the reference points with the circumference of the lunar disk and thus with its center.

To map the dark side of the Moon only space methods can be used, and cartographic continuity requires photography which will include part of the visible side of the lunar surface and part of its dark side in a single frame. /11 Naturally, it is those points on the visible side which are found near the edge of the lunar disk in observations from Earth that are photographed in such an instance. Determination of the selenographic longitude for these points may involve considerable errors, which then cause the longitudes of features on the dark side to be in error. Because of this, it was found that the longitudes determined from data of the Soviet and American spacecraft (Luna-3, Zond-3 and Lunar Orbiter) differed by up to 7°. In linear dimensions, this represents 200 kilometers. Of course, such discrepancies are not allowable, and they were eliminated in further investigations.

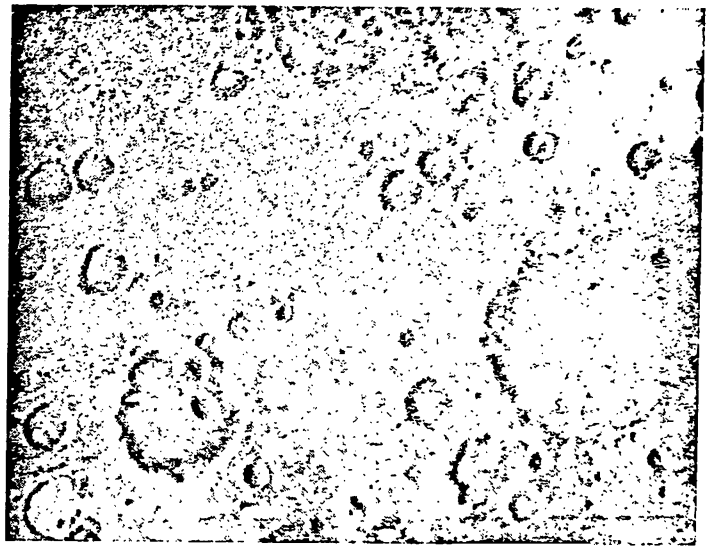

Figure 4. Part of the surface of Mars at a distance of 3500 km. Photograph taken by the unmanned spacecraft Mariner-6.

The achievements of the unmanned interplanetary stations of the "Mariner" series (Nos. 4, 6, and 7), which revealed numerous circular mountains very similar to such formations on the Moon, have /12 forcibly advanced problems which we call geomorphological problems with respect to Earth. The morphology of a planetary surface reflects its past history. The similarity in the surfaces of Mars and the Moon, of course, indicates a similarity of formation. Their differences, caused mainly by the existence of an atmosphere on Mars and the lack of one on the Moon, are of considerable interest. The total number of circular formations per square kilometer of the surface of Mars is the same as on the lunar continents, although small formations with diameters from 20 to 3 km are more numerous on the Moon. Since the formations that are less than 3 km in size are not distinguishable on the Mariner-4 photographs and not all objects with dimensions greater than 3 km (approximately up to 10 km) can be recognized on these photographs, we can only guess as to whether their small number is a result of observational selection, or is a result of their obliteration under the influence of winds, distortion from meteoritic impacts, or by thermal stresses. With Mars being near a ring of asteroids, we might expect a considerably greater number of circular mountains on it, but if this is not true and the efficiency of the above landscape obliteration is unknown, then the hypothesis of an endogenous or volcanic origin of the craters becomes plausible . No matter what the true situation is, all the detailed photographs of the Moon at close distance only strengthened the opinions of those who considered that the lunar landscape was formed under the action

Figure 5. Mars at a distance of 90 million km (Pic du Midi, France, 1967) and 920,000 km, July 29, 1969 (Mariner-6, below).

of both internal effects (vulcanism, tectonics) and external effects (incidence of meteoric bodies).

The different radioactivity of the various lunar formations obtained in the lunar orbits of our unmanned space stations Luna-10 and Luna-12 speaks in favor of the first hypothesis. This difference indicates that basic rocks predominate in the seas (basalts) and ultrabasic rocks on the continents. The first probably has a high amount of iron (the so-called ferrobasalts). As a whole, as chemical analysis of the lunar soil made by the Surveyor, the Luna-9, and the Luna-13 showed, the lunar surface rocks are the result of fusion. Analysis of the composition of the samples collected at the landing site of the Apollo-11 in the Sea of Tranquility revealed a rather high petrographic diversity and, in general, a significant similarity to igneous /13 rocks on Earth, if we do not consider /14 the very high titanium (TiO_2 up 10% by weight), Zr, Y, and Cr content with a significant sparsity of alkali metals Na, K, and Rb. These volcanic specimens contain numerous gas cavities, about 50% clinopyroxene, about 30% plagioclase, a large amount (up to 15%) of ilmenite and granular impregnations of olivine, and sometimes iron-nickel spheres. These can be included in the olivine-containing basalts. But there

are basalt specimens which contain no olivine. Under terrestrial conditions, basalt lavas are smoothly extruded.

Along with the basalts, the investigated lunar specimens contain breccia type rocks which consist of cohesive angular fragments less than 0.5 cm in size. Traces of microfractures and numerous vitreous inclusions can be seen here. Their structure is commensurate with the thesis that they were formed by the powerful impact of a body on the lunar surface, falling onto the Moon from outer space.

In general, the rocks collected on the Moon reveal traces of erosion (impact?) on the upper surface, whereas the lower surface has apparently remained unchanged. Analysis of the age of specimens from the Sea of Tranquility (for the potassium:argon ratio) indicates that they were crystallized from three to four billion years ago; that is, they are older than the most ancient of terrestrial rocks. According to the traces which cosmic rays have left in them, these specimens had been at a depth of more than a meter under the surface during their entire existence except for the last 20-160 million years; that is, they were ejected to the surface either as a result of meteoritic erosion or as a result of tectonic processes.

The fact that the upper cover of the Moon still lives and "breathes" today is indicated also by the optical phenomena repeatedly mentioned by observers during the time of telescopic observations of the Moon (such phenomena are numbered at about 600 over three-and-one-half centuries) and especially the generation of gases in the region of the crater Alphonsus mentioned by N. A. Kozyrev in 1958 during spectral observations. In order to reliably answer the question of the authenticity of rapid changes on the surface of a planet or of the Moon, we must have simultaneous observations at several astronomical stations separated from one another in longitude by 90-120° and directly connected with one another by modern communication facilities. /15

Figure 6. Surface of the Moon, taken at a close distance with a television camera on the unmanned spacecraft Luna-9.

We should mention that the combined influence of the internal and external factors in the formation of the lunar landscape (just as for Mars) is apparently inescapable, since the impact of a large meteorite will arouse volcanic activity in that region.

The number of craters on the Moon is so high that they can never be considered to be only the result of the impact of asteroids and large meteorites, which occurs rather rarely. It would be more proper to credit the formation of the craters to that era when the Moon was just forming and many planetesimals, as yet unabsorbed by the planets, were moving around it. When the Moon absorbed them, circular mountains of various dimensions were formed. Gradually a state of saturation was established, when any new impact would annihilate the older craters and create new ones. In fact from one (in time) impact several ejections may occur which either form a chain of several craters, or only one which is /16 elongated in the direction of the ejections — as, for example, the crater Schiller in the southwest part of the visible lunar disk. The large number of small craters arranged around the crater Copernicus are undoubtedly of secondary origin. They were formed as a result of the explosive dispersion of lunar matter when the basic crater was formed.

These craters can be easily discerned on the dark background of the Oceanus Procellarum. This same dark coloration of a different degree of saturation is possessed by all the seas on the Moon, their surface is comparatively smooth, and they are either devoid of craters, or have very few. The reason for this sparsity is the age of the seas. These are young formations, formed about two billion years ago, on which numerous large

bodies, preserved until the later stages of development of the solar system, left traces of the impact. However, in the very youngest formations, such as, for example, the craters Tycho or Aristarchus, the surface is very uneven and covered with large fragments. With time, they will be broken up and acquire a fine structure on an overall smooth background, and only massive impacts will disturb this picture. New impacts will disturb the already existing formations by different means, that is, by direct impact or by secondary impacts during dispersion. The lunar surface has undergone events of such nature many times during its existence, and very ancient objects have gradually disappeared. Only the largest of them, many hundreds of kilometers in thickness, can still be traced in our time.

Although on the Moon, in contrast to the Earth, the changes on the surface take place with extreme slowness because of the absence of weathering and erosion, the Moon, nevertheless, is not a museum. It is externally vulnerable, and the effect of external factors continuously changes its face. Therefore, we can understand that those lunar formations, whose age exceeds four and one half billion years, have not been preserved up to the present.

Craters are also encountered on the Moon which are similar to volcanoes on the Earth (around this same Copernicus), and sometimes they are quite numerous. It is assumed that at times lava flows from them, but these processes are of a local nature and determine the lunar landscape to only a small degree.

The soft landing on the Moon of the unmanned space stations, Luna-9, Luna-13, and the Surveyors, not only gave information on the chemical composition of the lunar cover, but also established its macroscopic structure, that is, finely crushed bunches, dust particles (about 10 μ), in which small and large fragments and basic lunar rocks are imbedded. Contrary to former concepts, they are weakly bonded and by no means form strong strata, consisting of minute grains. Very fine dust, in fact, does cover everything on the Moon — the finely crumbled surface and rocks, but the supports of the /17

"Eagle" (see Figure 1) sank only 5-7 cm into the ground and the astronauts' feet sank only several millimeters. In an attempt to sample depth, a steel tube was sunk 5-7 cm without difficulty, and only with a great exertion of force was a depth of 20 cm reached, but the core samples taken were found to be finely structured. The crew of Apollo-12, which landed in Oceanus Procellarum, encountered a more friable surface layer. The density of the friable surface material of the Moon, as the samples showed, was altogether 0.8 g/cm^3, and beneath them, starting at a depth of 5-10 cm, the density reached 1.5 g/cm^3. Finally, the density of the rocks and stones lying on the surface was equal to approximately 2.8 g/cm^3. As radio observations of the Moon show, the density of its surface layer gradually increases with depth and reaches the density of the underlying rocks at a depth of one to several meters. The surface layer is thicker in the seas — up to ten meters. With all the similarity between the Martian and lunar landscapes, we can hardly expect the same surface structure on Mars. The existence of an atmosphere makes it impossible for the dust particles to adhere, as this is inevitable in a vacuum. The surface of Mars must have a more friable structure, and this is confirmed by radar observations which indicate an incomparably greater smoothness on it than on the Moon (see page 17).

If it has become possible to obtain information, using unmanned space stations, on the chemical composition and also to study the structure of the upper cover of the Moon, then its petrographic compositions are derived mainly on the basis of analogies from photometric, spectrophotometric, and polarization observations. These analogies in the majority of cases are /18 loose, since the result is usually ambiguous, and, furthermore, the color /19 varies depending on the degree to which the matter is broken up and depending on the ultraviolet radiation or proton radiation. So, for example, the almost universally accepted conviction that the surface of Mars is composed of limonite ($Fe_2O_3 \cdot nH_2O$), based on the similarity of many spectrophotometric and polarization characteristics, is encountering difficulty today, since with advanced investigations new characteristics are being discovered that do not coincide for Mars and for limonites.

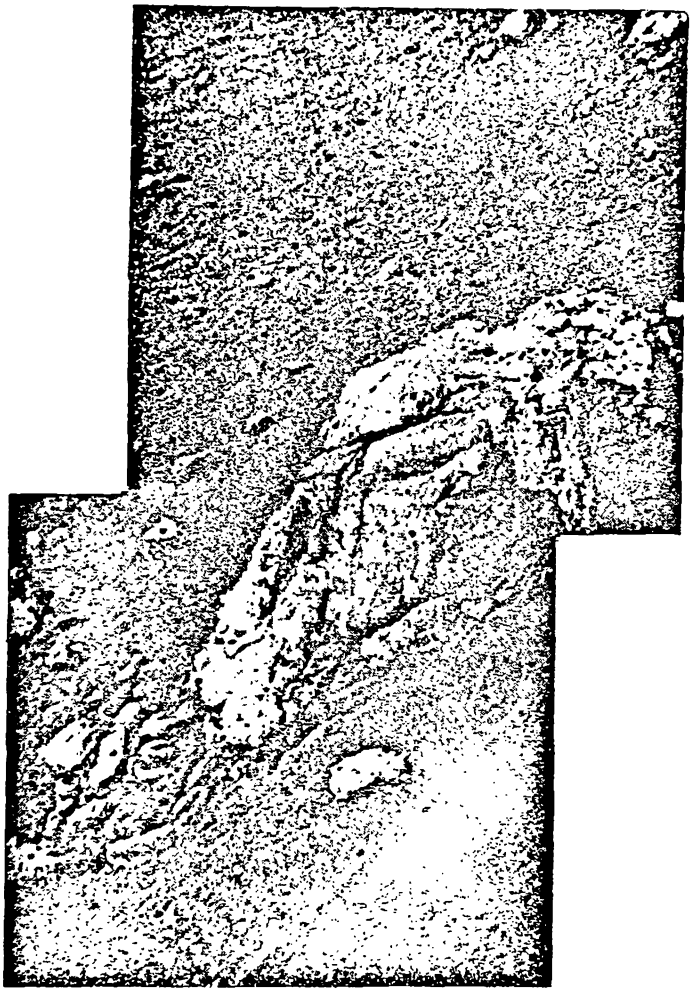

Figure 7. Large (0.5 m) rock on the surface of the Moon (Photograph taken by the unmanned spacecraft Surveyor-1).

No less ambiguous are the results of radio observations of the natural thermal emission from the planet in various ranges. Emission at long waves comes from the subsurface strata. The phase lag in the maximal or minimal temperature and the variation in the mean diurnal (on the Moon — monthly) temperature with wavelength (or what amounts to the same thing, with depth) gives the possibility of judging the thermal conditions of matter on the planet's surface layer at various depths, and its thermal and electrical properties. Unfortunately, only the rather complicated quantity, the coefficient of thermal conductivity $\gamma = (\chi\rho c)^{-1/2}$, is amenable to direct determination; this coefficient connects the coefficient of thermal conductivity χ, density ρ and specific heat c of the material. As yet this method has given specific information only about the Moon. Averaging which is too broad is obtained for the planets over practically the entire hemisphere of the planet; it is difficult to eliminate the influence of the atmosphere. In its application to the Moon, this method gave a result that is in accordance with other methods; its surface is composed of finely crushed rocks. The temperature gradient is sizeable, thus indicating a heat flux from the depths of the Moon. Using reasonable values for two of the three quantities χ, ρ, c, we

can find the third and then seek rocks which have the appropriate properties. However, in this case there is still a wealth of choices to be made.

Narrowing the range of solutions is only possible after a systematic direct investigation of the various sites on the lunar surface becomes possible with the aid of spacecraft that have landed there, including manned craft. Comparison of the radio observations and the results of direct analyses will make it possible to standardize the radio observations, that is, to establish a correlation between real rocks and their radio emission. /20 Later this standardization can be applied to an analysis of the radio observations from Mars and Mercury. The use of radar methods has been of substantial aid for this purpose; these methods make it possible to study the reflectivity of the component rocks.

The radar technique is effective also in solving the question of the degree of roughness of the planetary surface. Two mechanisms operate in the reflection of radio waves, that is, quasimirror reflection from large-scale irregularities (without disruption of coherence) and disordered scattering on small-scale heterogeneities, whose dimensions are on the order of magnitude of the wavelength. The first is performed along the normal, since the transmitting and receiving stations either coincide or may be spaced over the Earth, which even from the Moon is visible at an angle less than 2°. If the slopes[1] on the planet are generally not high, coherent reflection will take place only from a small region in the center of the disk, such that the site of the reflection may be established with complete confidence. Scattering on small surfaces is disordered, strongly damped and unpolarized, which permits distinguishing it without difficulty. On a comparatively rough scale ($\lambda \approx 70$ cm) the smooth slopes are 3° for Mars, 6° for Venus, and 10° for the Moon and Mercury. As applied to Mars, the photometrically processed photographs obtained by Mariner-4 led to the conclusion, from fluctuations

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[1] We mean here the inclinations of the lateral slopes of the surface formations toward the horizontal plane.

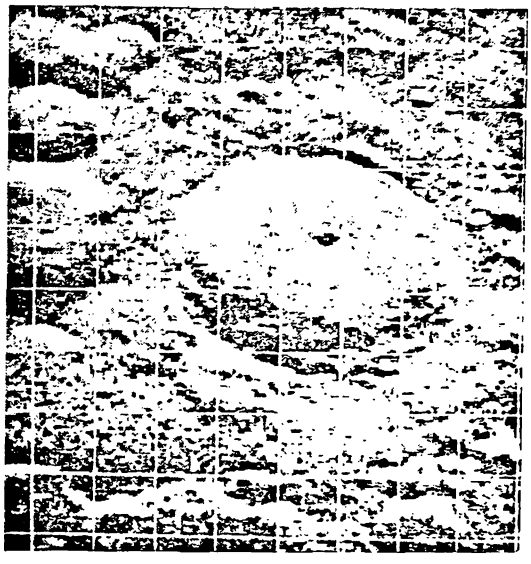

Figure 8. Radar picture of the vicinity of the lunar crater Tycho, taken at the radioastronomy observatory at Haystack. The picture permits distinguishing details having a dimension of 1 km. Unlike an optical picture, the details here are differentiated from one another based on their ability to reflect the radio signal sent from the Earth (wavelength of 3.8 cm). Not only is the reflectivity in itself manifested, but also the slopes of the reflecting elements to the line of sight, since large details have a specular reflection and if the corresponding surface is not perpendicular to the incident beam, it is either not reflected back in the same direction, or a weak diffusely reflected signal will be obtained.

in brightness as a function of the angle of elevation of the Sun, that on a scale of 3 km and higher the slopes in the irregularities lie in the range of 1-3°, although on the slopes of the craters, inclinations of up to 12° are possible.

Polarization of radio waves, reflected from the edge of the planet's disk, as well as from its natural radio emission, makes it possible to determine the dielectric constant of the planetary matter and thus narrow the scanning range for the material comprising the surface.

As applied to the Moon, the complilation of the radar chart was found to be fully successful. At a wavelength of λ = 3.8 cm, a resolving power on the order of 1 km was attained, which approaches the resolving power of optical astronomy. Figure 8 shows such a map, compiled at the Haystack station (USA) and showing the distribution of the reflectivity (by no means light and dark) in the region of the crater Tycho. In order to obtain similar results with respect to the planets, much more powerful telescopes are required (at least two orders of magnitude larger), since the planets are two orders of magnitude farther away than the Moon; correspondingly the directionality of the radio antenna must be raised by two orders. In this case

/21

the same strength of the reflected signal will not be attained; this signal grows only in proportion to the root of the fourth power of the antenna cross section. Even today, the sensitivity of the apparatus used in radar is admirable; the radio impulse reflected by Venus is so weak that it is impossible to find it directly. It is discernable only by complicated computational analysis. Its energy is similar to the work of one step of a mosquito. /22

Mars, whose surface has been most studied after the Moon, leaves a number of unresolved problems, among which the important ones are the questions concerning the nature of the polar caps and the cause of seasonal variations in them. In this connection, we have not mentioned the nature of the canals on Mars, since after almost one hundred years of discussion, the "public opinion" of the astronomers tends to believe that the canals are the result of schematization in drawings (or examining photographs) of Mars. It is an involuntary geometrization introduced by the observer into the picture of the distribution of extremely weak and unclear details.

After obtaining photographs of Mars at close distances with the aid of the unmanned spacecraft Mariner-4, Mariner-6 and Mariner-7, which revealed no signs of such canals, the question as to the canals on Mars can be considered "closed".

As we know, the atmosphere of Mars contains water vapor in a small amount, and mainly carbon dioxide (see below). This gives a basis for assuming that the polar caps of Mars consist of snow or of solid carbon dioxide. The temperature of the Martian surface at the poles allows either assumption. The spectral observations favor snow. In the light reflected from it there are absorption bands with a wavelength of about 1.4 and 1.9 μ. The same is observed in the spectrum of the polar caps of Mars. The character of the light polarization reflected from the polar caps of Mars is the same as in hoarfrost which is formed at low temperatures by means of direct conversion of the water vapors into the solid state. The reverse process, taking place with heating of hoarfrost, also leads to sublimation from the

solid state, without thawing into the gaseous state, and the remaining hoarfrost assumes a porous structure. Its very weak polarization is similar to that observed at the polar caps of Mars.

In addition to this, we must remember that in the Martian atmosphere carbon dioxide is predominant and the very low temperature at the Martian poles (about 150° K) does not permit the carbon dioxide to remain in a gaseous /23 state. Precipitation of the overwhelming part of it in the form of "snow" and dry ice is unavoidable. Therefore, the main component of the polar caps of Mars is carbon dioxide mixed with water in the solid phase. A very small admixture of snow is necessary in order that significant bands are found in the reflected light with wavelengths of about 1.4 and 1.9 μ.

As far as seasonal variations in the dark "seas" of Mars are concerned, which have basically the same color as the light "continents", only with a lesser albedo, as we well know they are often attributed to the growth of plants with onset of the warm season, melting of snow, and moistening of the soil. Included in the sources of moisture, we have mentioned mineral water since all of Mars in terms of its mean temperature (see below) is located in a state of permafrost, thawing only at the top and for a short time in the middle and lower latitudes. It is difficult to call these processes anything other than biological processes which might vary the structure of the upper cover of the planet's surface as a function of time of year. In the absence of, or extreme sparsity of, free oxygen on Mars, vegetation there may exist only in the simplest forms. Spectral investigations, unfortunately, have not helped solve this question, but the polarization investigations which indicate, first of all, the structure of the reflecting surface foster the assumption of mass breeding of small organisms in the form of opaque granules including sporous plants — algae, Cetraria caccullata, and fungi. The precipitation of crystal formations would give a completely different polarization picture.

The extraordinarily low contrast of the individual segments on the photographs of Mars, obtained by Mariner-4, fully correspond to the picture

long-mentioned by Earth observers, that is, the extreme "grayness" and the insignificance of the details on Mars during the winter season. Mariner-4, orbiting Mars, photographed primarily its southern hemisphere, when winter prevailed there. Mariner-6 and Mariner-7 were in the most favorable position — their photographs were much better: Mariner-6 photographed mainly the northern hemisphere where at this time it was early fall, and Mariner-7 photographed the southern hemisphere where it was early spring.

Radar observations of long-range reflection of the emitted signal reliably revealed the irregularity of the relief, reaching 12 km on Mars. We should not be surprised at this. The differential in heights on the small Moon is not any less. If the depressions on Earth were not filled with the ocean, the height differential externally observable between the Himalayas and the Phillipine trough would reach almost 20 km. But on Venus, radar did not reveal any altitude difference greater than 2 km. It is true this refers to the topography along a certain parallel, for which the Earth was at zenith during the observations. On other parallels, the situation may be completely different! /24

In finishing this examination of the questions involving the structure of planetary surfaces, we should emphasize that the tempting possibility of making an analogy here with the structure and composition of meteorites is dangerous, since it is quite doubtful that meteorites are fragments of large planets. They have never been subjected either to the effect of very high pressures or to that of high temperatures.

Determination of the absolute values of the temperature of the planet's surface is very specific. Optical methods based on measurements in the infrared band of the thermal flux, coming to us from the planet, give a comparatively high degree of resolution by cross section. In particular, on the Moon numerous "hot" points have been detected which are revealed by slow cooling at sunset or in the process of lunar eclipse — this is direct proof of the absence of a thick heat-protective dust cover at these sites.

But only as applied to the Moon and Mercury which have no atmosphere does this path lead directly to the target. As applied to Venus, the measurements of thermal flux in infrared rays gave a temperature of about 240° K, referring to the upper troposphere rather than to the surface, and as applied to Mars — a surface temperature, slightly distorted by atmospheric influences. Measurements of thermal flux in the radio band are free of this disadvantage to a much larger degree, but they are also not without fault. This is because, in the centimeter and millimeter bands, the radio waves are absorbed in the atmospheres of the planets, and in the decimeter and decameter band the ionosphere, if it is sufficiently dense, may introduce disturbances.

It is just such a situation that was created in interpreting the /25
measurements of the radio emission originating from Venus. At wavelengths from 3 to 10 cm, the measurements give a brightness temperature up to 700° K and above, but at the shorter wavelengths it is much lower, below 300° K. At the 21 cm wavelength, a drop in temperature is also observed. A ten-year discussion accompanied by ever newer and newer measurements have led the majority of astronomers to the conclusion that only the measurements in the 3-10 cm band pertain to the solid surface of the planet. The shorter waves are absorbed strongly in the atmosphere; therefore, the temperature of 300° K pertains to the upper atmospheric layers. However, only the direct temperature measurements in the atmosphere of Venus carried out in the brilliant experiment of the Soviet unmanned spacecraft Venera-4 — and the proofs thus found that Venus has no significant ionosphere (it exists only on the daylight side and is apparently caused by solar x-ray radiation) — finally convinced everyone that the surface of Venus is in fact very hot, and placed before theorists the problem of explaining this fact.

Measurements on the large radiotelescope at Pulkovo, the flight of the American unmanned craft Mariner-2 near Venus and, finally, the interferometric measurements with a high resolving power at the 10 cm wavelength have all made it possible to study the temperature distribution across the disk of Venus, although it is true it is only approximate and the results obtained by various means are not without contradictions.

The temperature on Mars was found to equal approximately 200° K which is the mean temperature across the disk, in a wide range of radio waves (3 mm - 20 cm). It would be interesting to trace, by radio measurements with high resolution, the existence of relationships between polarization of the emission and the progressive seasonal darkening of the Martian seas, visible during polarization observations in the visible band.

Measurements of the natural radiation from Mars in the infrared band gave results similar to the results in the radio band, but not coinciding with them: for those places on the equatorial belt of the planet's surface where the Sun is at the zenith (subpolar region) a mid-day temperature was found in the range from 250 to 280° K at aphelion, and about 300° K at perihelion. Such differences should not be surprising, since the orbit of Mars is rather eccentric and at its perihelion Mars is located significantly /26 nearer the Sun than at aphelion. The latest, more reliable measurements give lower values, which correspond better to the radio measurements — for example, for the entire illuminated hemisphere of Mars a mean temperature of 225° K (at aphelion) was found. Furthermore, the temperature of the Martian surface undergoes very strong variations in the course of short days ($24\frac{1}{2}$ hours). During the day there, shortly after noon, it reaches a maximum of about +20° C; in the morning after the nocturnal radiation of heat into outer space, the temperature drops to -60° C. The reason for such a rapid cooling undoubtedly is due to the low density of the atmosphere (see below) that is incapable of retaining the natural radiation of the planet. The latest measurements by Mariner-6 revealed a new temperature of 150° K at the polar caps on Mars.

New measurements of Mercury in the infrared band give a temperature of 620° K for the daylight side. The dark side is no hotter than 150° K, but also is somewhat colder, which does not agree with the idea that there is no atmosphere on the planet and with the new correct value for the period of rotation, for which the solar days last 176 Earth days. In the event there is no atmosphere, the temperature during the night would have to sink much lower and then, in measuring the integral temperature across the disk of

Mercury, a notable phase effect would be observed — that is, a dependence of the measured temperature on the value of the unilluminated (night) part of the planet's disk. But the phase effect on the temperature of Mercury is very weak.

3. PLANETARY ATMOSPHERES

The existence or the lack of an atmosphere is strongly manifested in the many physical properties of the surface layers of a planet, that is, in its thermal conditions, formation of the planet's landscape, possibility for the evolution of life, etc. Furthermore, the chemical composition of a planet's atmosphere gives signs as to the past history of the planet. /27

A planet's atmosphere is revealed by a fading of brightness toward the edge of the disk, by blurring, by clouds, etc., when simple telescopic examination of the planet is involved, but for quantitative determinations we must have measurements — photometric, polarization, and spectral. The photometric measurements are the simplest, but their interpretation will not provide a completely unequivocal answer, because the presence of suspended particles and aerosols in the atmosphere will somewhat complicate the theoretically clear photometric effects of a purely gaseous atmosphere. In particular, it will lead to an exaggeration of the thickness of the atmospheric layer. The same can be said of polarization measurements. Neither measurement procedure will give any indication of the chemical composition of the atmosphere.

Incomparably more accurate and complete information is given by spectral analysis, both in ground observations, and especially when receiving equipment is launched into the stratosphere or completely beyond the confines of the Earth's atmosphere. Still more information is given by chemical analysis of the atmosphere carried out by equipment penetrating it, such as was done by the unmanned craft Venera-4, Venera-5, and Venera-6.

A summary of our current knowledge on the chemical composition of planetary atmospheres is given on Table 1 on page 26.

TABLE 1. GASES WHOSE PRESENCE HAS BEEN DETECTED IN THE ATMOSPHERES OF PLANETS AND SATELLITES

Planet	Gases	Planets	Gases
Mercury	CO_2??	Uranus	H_2, CH_4
Venus	CO_2!!, CO, N_2, H_2O, O_2, HCl, HF	Neptune	H_2, CH_4
		Pluto	No data
Earth	N_2!!, O_2!, H_2O, Ar, CO_2 Ne, He, CH_4, Kr,	Satellites of Jupiter	No data
Mars	N_2O, H_2, O, O_3, Xe CO_2, CO, H_2O, CO_2^+ ion, H, C, O atoms	Titan (satellite of Saturn)	CH_4
		Triton (satellite of Neptune)	No data
Jupiter	H_2, CH_4, NH_3		
Saturn	H_2, CH_4, NH_3(?)		

There is every basis for assuming that a large amount of helium exists in the atmosphere of Jupiter. But its resonance lines are found in the far ultraviolet band, and the necessary excitation sources are lacking for the appearance of nonresonance lines, taking place from the excited levels. In precisely the same way, the existence of molecular nitrogen on Venus would be impossible to establish by means of ground observations, since its clearest spectral characteristics are found in the ultraviolet spectral band, /28 which are completely blocked by the Earth's atmosphere. The existence of N_2 on Venus was first established by Venera-4, just as O_2 and H_2O, which had previously been detected only hypothetically.

The unmanned space stations Venera-4, Venera-5, and Venera-6 reported reliable quantitative data: the equipment installed on them showed that the atmosphere of Venus is very hot, and in its composition carbon dioxide occupies about 97 $\pm$4%. The gases N_2, O_2, and H_2O must be assumed as merely

impurities. The numerical data should be assumed as approximate, since it is still not clear as to which level above the surface of the planet they refer.

If we assume that Venera-4 discontinued transmission of information at an altitude of about 20-25 km, it is precisely to this level of Venus' atmosphere rather, than to its base, that we must attribute the measured values of T = 540° K and P = 18.4 atm. Then by extrapolation, we can find, for the surface of Venus, an atmospheric pressure near 100 atm and a temperature above 700° K with no unusual fluctuations from day to night. Almost the same data were reported by Venera-6: in the altitude range from 48 to 10-12 km the pressure varied from 0.5 to 27 atm, and the temperature from 300 to 600° K. If these data are extrapolated according to adiabatic law, then for the surface of Venus we will obtain a pressure of 100 atm and a temperature of about 770° K. Similar data are obtained on the basis of ground radioastronomical observations. /29 The data from Venera-5 differed rather strongly from these results. The reason for these deviations is still not clear. If we take the mean value from those obtained by Venera-5 and Venera-6 for the amount of water vapors equal to 0.05% over the atmosphere as an average, then their relative content in the atmosphere of Venus is found to be the same as on Earth, but the absolute value is found to be two orders of magnitude higher. However, in the Earth's oceans the amount of water contained is five orders of magnitude greater than in the atmosphere. Therefore, we can confirm that the amount of water on Venus is significantly less (by three orders of magnitude) than on Earth. The same can be said also about oxygen. As far as the absolute content of carbon dioxide in the Venusian atmosphere is concerned, then it would approach in order of magnitude that which would exist in the atmosphere of Earth if all its carbonate rocks were to release the CO_2 bound in them. To make a full comparison of the atmospheres of Earth and Venus, we must know the amount of virgin CO_2 and H_2O, which is constantly leaving the depths of the Earth into the atmosphere by volcanic eruptions. /30 On the whole, if the entire atmosphere of the Earth is assumed to be the result of the generation of gases from the solid crust ("degassing") and we consider

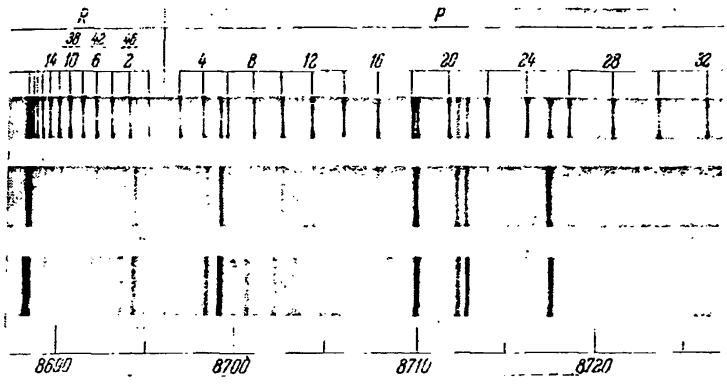

Figure 9. Spectrograms of Venus (upper), Mars (middle), and the Sun (bottom) (taken through the Earth's atmosphere) in the 8690-8730 Å band, occupied by a CO_2 carbon dioxide molecule band, the lines of which (they are scaled at the top) are very sharply visible in the spectrum of Venus, much weaker in the spectrum of Mars and totally invisible in the spectrum of the Sun. The other strong lines of the spectrum are formed either in the atmosphere of the Sun or in the atmosphere of the Earth.

that no chemical interaction with the crust and the biosphere has taken place, then we find a composition that is similar to that on Venus (and Mars) with the exception of the excess of water on Earth which requires a separate explanation.

Thus, the atmosphere of Venus also has a secondary origin, but probably with no biosphere. For the beginning of life on Earth, a reducing atmosphere was required (for example, with an abundance of methane CH_4, hydrogen H_2, etc.). It would be interesting to seek prebiological organic molecules in the reducing atmospheres of the major planets. It may be that the absorptions at $\lambda\lambda$ 2600 and 2100 Å, detected in the spectrum of Jupiter, have precisely such an origin.

Bearing in mind the difficulties in observing Venus from Earth, following from the fact that it is a minor planet which is near the Earth only when its dark side is mainly turned toward us, we must not exaggerate its cloud layer. In fact, photographs of the Earth, obtained in the past two to three years from the distance of the Moon to the Earth under favorable illumination conditions, and also from satellites at closer distances, can be interpreted by us only with difficulty and we are familiar with the map of the Earth, since it seems to be so covered with a cloud cover. Although the albedo of Venus is much greater than that of Earth, nevertheless, the veil of the Venusian clouds is not dense, which is proved by the diversity in temperatures

found by spectroscopic measurement of the CO_2 bands on Venus: the temperatures are obtained in a wide range from 215 to 445° K, obviously depending on how free of clouds is the site of the planetary disk that is spectrographically measured, and in the same manner at what great atmospheric depth the observable spectral bands originate.

With the very slow rotation of Venus, its thick atmosphere must obey forms of circulation that are completely dissimilar to those in the Earth's atmosphere. Theoretical study of this phenomenon and its proof by observations are of the greatest interest. However, the observations of Venus have established one type of atmospheric motion, similar to those on Earth, and judging from the motion of the dark formations in the cloud layer of Venus, /31 the rotation period of the atmosphere at this level comprises four Earth days in the same (inverse) direction as the rotation of the planet itself. This indicates winds of great force in the upper troposphere of Venus, moving at a velocity up to 100 m/sec in the direction of the planet's rotation.

Now we understand in rough outlines the atmosphere of Venus, but the details remain very unclear, including the nature of the cloud cover on /32 Venus and its role in the transport of radiation from the Sun to the surface of the planet and back into space. Now that we have proved the existence of water on Venus, due to the experiments with the unmanned spacecraft of the Venera series, more than ever we can assume that the clouds on Venus are of water. This is also indicated by the temperature of the cloud layer ($\sim$-30°C). But we have neither photometric nor spectroscopic proof of the aqueous nature of the cloud layer on Venus.

Motions in the lower atmosphere of Venus where no instruments have yet reached are completely unknown, as are the thermal conditions and illumination. Ground observations are in no position to answer this question, so that we must place our hopes in future experiments with equipment launched into the atmosphere of Venus.

Figure 10. The Earth at a distance of 70,000 km. Photograph obtained by the Soviet unmanned spacecraft Zond-7.

Theory, by the way, does permit answering one question, which had formerly caused much argument. This is the ability of the Venusian atmosphere by means of one of its effects, the greenhouse effect[2], to maintain a temperature of the planet's surface and lower atmosphere at a level of 700° K or higher. Now the justifications for the greenhouse effect on Venus have been found. As soon as the huge amount of carbon dioxide and a sufficiently large amount of water vapors on Venus were proven, its high absorption power in the near infrared band of the spectrum was in a position to retain the greater part of the natural radiation from the planet and in the same manner maintain the temperature at a high level (see below, Section 5). There is no need for either a large influx of internal heat from the planet or even of strong volcanic processes (they are accompanied by the generation of large amounts of sulfur dioxide SO_2, but this gas has not been observed on Venus).

With respect to the atmosphere of Mars, for some time we have been confident of our knowledge, since this atmosphere is rarefied and we can look right through it. It is true that until quite recently the role of

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[2] For greater detail, see Chapter 5.

light scattering by aerosols was underestimated, and we have overestimated the amount of atmospheric pressure on the surface of Mars and assumed it to be equal to 80-100 mbar, whereas its correct value is near 10 mbar (probably less than more). It is just such a value that is given by measurements of different CO_2 absorption bands, carried out on the Earth, and also investiga- /33 tions of the damping of radio emission of the unmanned spacecraft Mariner (see below, Section 5) in going behind the planet Mars. The difficulties arising in interpreting the spectral and photometric measurements rest mainly on the impossibility of taking into account the role of aerosols in the scattering of light. It is quite probable that the atmosphere of Mars is significantly colder than its surface. This is indicated by the estimate of temperature from the structure of the atmospheric spectral bands on Mars and from the results of radioscopy of the atmosphere by radio waves.

Cloud formations on Mars are an ordinary phenomenon, but quite variable. Here dust storms and haze are observed. As a rule, the Martian atmosphere strongly scatters violet rays, and when Mars is observed through blue or violet filters, very little can be seen. But a blue clearing sometimes exists in these rays also, and then the atmosphere of the planet is especially transparent. In its random nature, such a transparency was characteristic of the entire atmosphere of Mars at the time when Mariner-6 and Mariner-7, flying near it, photographed its surface. Recently the "violet clouds" on Mars have been found to be similar to terrestrial noctilucent clouds. But we should not be deluded by this comparison. Its cognitive value is not very great. It is sufficient to recall that arguments are still going on concerning the nature of terrestrial noctilucent clouds.

As far as Jupiter's atmosphere is concerned, although for the past several decades there has been some information about it, much remains completely enigmatic. The bands visible on Jupiter, of course, are cloud formations, the nature of which can be hypothetically established based on theoretical arguments. The basic cloud layer consists probably of solid particles of ammonium hydrosulfide (NH_4HS) and small drops of an ammonia solution in water (NH_4OH). The richness of the colors, mainly reds and

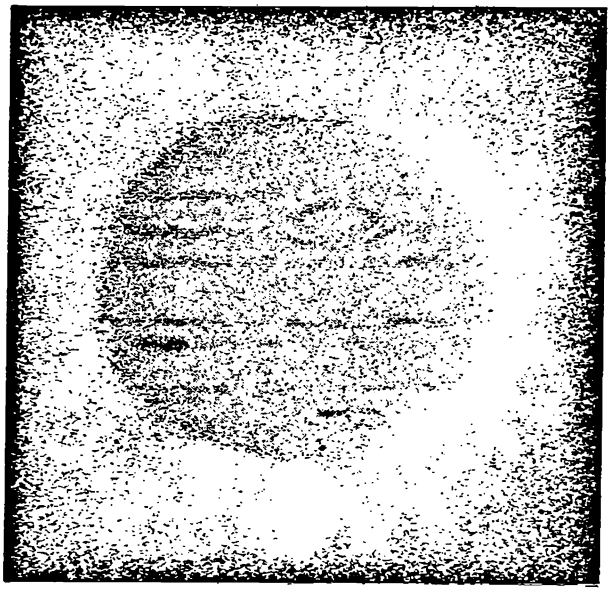

Figure 11. Photograph of Jupiter, taken on February 16, 1968 through a green light filter.

oranges, is created by cyanides of HCN and C_2N_2, which by polymerizing and converting to the solid state, assume chemical stability. In the laboratory these intensely colored compounds are formed by electric discharge in a mixture of methane and ammonia (in the absence of oxygen). Higher up, above the basic massive clouds, up to the troposphere, crystalline particles of solid ammonia are suspended which form a light haze. The haze /34 is observed only by using specific methods, and is found to be a variable phenomenon. In particular, Jupiter has its own type of "polar caps" of these particles, whereas Saturn has none.

Thus, in general, we can explain the diversity in colors and shades visible on Jupiter. In particular, the dark bands of Jupiter are not gaps in the cloud layer, but are simply clouds having a different composition. All of these are comparatively high formations at the level of which the pressure comprises several atmospheres (2-5 atm), and the chemical composition of the atmosphere as determined from spectral observations is the following: methane (about 100 m-atm)[3], ammonia (on the order of 10 m-atm), hydrogen /35 (85,000 m-atm). Based on theoretical arguments the atmosphere of Jupiter should have an abundance of helium (about 26 km-atm), but it is not amenable to observations from Earth. These quantitative estimates are quite unreliable,

[3] 1 cm-atm characterizes the amount of gas in a column having a height of 1 cm and an area of 1 cm^2 at a pressure of 1 atm and a temperature of 0° C; 1 m-atm = 100 cm-atm; 1 km-atm = 1000 m-atm.

since the role of multiple scattering, which certainly is effective in the atmosphere of Jupiter, is unknown. This is particularly indicated by the fact that absorption in the methane bands is not amplified toward the edge of Jupiter's disk, but rather is diminished. Therefore, the numbers given above in meters-atmospheres refer to the gas content in the atmosphere of Jupiter not only above the cloud layer, but inside this layer as well, along a complicated and intricate path of light quanta which are multiply scattered in the clouds.

Bearing in mind the low temperature of the upper atmosphere of Jupiter, we have no right to expect indications of water vapors in its spectrum, but as to whether they do, in fact, exist in the lower atmosphere, which is warmer, is an important and interesting question, since this would incidentally solve the problem of the existence of oxygen on Jupiter. Free oxygen or the presence of a large amount of free hydrogen obviously does not exist. No less interesting would be the establishment of carbon dioxide in the atmosphere of Jupiter, which must also be destroyed by frost in the upper atmosphere.

Temperature measurements in the infrared rays gave values of 150 and 128° K at wavelengths of λ 20 μ and λ = 8-14 μ, respectively. Radio measurements in the range $\lambda < 3$ cm gave approximately the same values in the range of 110-150° K. At the same time, the equilibrium temperature, that is, the temperatures at which the heat received from the Sun and the heat emitted by the planet into space are quantitatively equal, is 110° K for Jupiter — that is, significantly less than the measurements give. Consequently, the internal heat of the planet reaches the surface of Jupiter which we observed and increases the heat flux leaving it by no less than 20%.

In measuring the emission from Jupiter in the radio band, there are indications that the temperature increases with depth, and the variable intensity of emission points to atmospheric activity. This is also indicated, although not explained, by the appearance of "hot shadows" — at a wavelength of λ = 10 μ an increase in temperature in the shadow cast on the planet by its satellites.

A decisive event in observational astronomy is the obscuration by a planet during its travel across the sky of one of the stars of sufficiently bright to be observed at the time of extinction as it passes beyond the atmosphere of the planet approaching it. For the past ten years only three such cases have been registered: obscuration by Venus of Regulus in 1959, by Jupiter of σ Aries in 1952 and by Neptune of a seventh magnitude star BD-17°4388 in 1968. The photometric observations of the star during obscuration make it possible to determine the altitude of the uniform atmosphere H of the planet at various levels[4] and then to find either molecular weight or temperature, if the other quantity is known[5]. If the temperature value of 100° K, which prevails in the upper layers of Jupiter's atmosphere is proven, for which H = 8.3 km has been found, then the molecular weight of its upper atmosphere is near 3.8, which is similar to the molecular weight of helium (4.0), which has not been spectroscopically detected in the atmospheres of the planets. But hydrogen H_2 (molecular weight $\mu = 2$) has been detected on Jupiter in huge amounts, while the heavier CH_4 and NH_3, on the other hand, have been found in relatively negligible amounts. Therefore, the molecular weight $\mu = 3.8$ indicates that, in terms of volume, helium makes up quite a significant part of Jupiter's atmosphere; we mentioned this earlier. When our radar equipment is found to be adequate for locating Jupiter's satellites, radioscopy of its atmosphere will become a commonplace event, and will give much more information concerning the scale of altitudes, horizontal movements in it, and its dielectric properties. /36

Jupiter seems to be the most enigmatic of the planets. These enigmas begin from its visible surface and extend both to the deepest and to the uppermost layers, its exosphere.

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[4] The quantity H is also often called the "scale height", since it is the difference in altitudes corresponding to the decrease in atmospheric pressure by a factor of e (2.718...).

[5] For greater detail, see Chapter 5.

The different angular rate of rotation of the various zones of Jupiter depending on the their distance from the planet's equator (equatorial acceleration) can be comprehended and probably theoretically interpreted based on the fact that the planet's atmosphere is very large, its rotation is very rapid, and the centrifugal and Coriolis accelerations are high. Spectral observations have revealed a strange incongruity between the linear /37 rotation velocity of the clouds and the gas component of Jupiter's atmosphere. Sometimes it seems that the ammonia and the methane do not participate in the planet's rotation; that is, the gas masses move counter to the rotation, which obviously may be accomplished only at a level other than the level of the clouds, and in any case, indicates a certain unusual type of atmospheric circulation. But such an exceptionally stable formation as the Red Spot also has its own special rotation period, so that this atmospheric formation moves relative to the surrounding atmospheric masses, which in the vicinity of the Red Spot have velocities up to 100 m/sec. There are indications that the atmospheric circulation takes place around it with a period of 12 days.

This and many other factors indicate a tremendous atmospheric activity on Jupiter, but the nature of the activity is not clear. The role of the Sun in the thermal conditions of the planet even with a small penetration into the atmosphere of Jupiter is small — the heat flux from the Sun there is 27 times less than on Earth, and a significant part of it is reflected into interplanetary space. The rapid rotation makes the time variations in solar radiation insignificant during the day, and the small inclination of the planet's axis and the almost circular orbit of Jupiter makes the variations small during the year. We can understand the latitude distribution of the atmospheric processes, because of the latitude dependence of solar radiation and acceleration of gravity is constantly in operation on Jupiter. In addition, to the latitudinal heterogeneities there are considerable longitudinal heterogeneities.

Deeper into the atmosphere of Jupiter, we encounter ever-increasing temperature and pressure. This latter may reach values at which H_2 and He

are converted into the solid state; at various latitudes, such a conversion will take place at different depths, and there must not be any longitudinal variation here. Thus, the question arises as to whether those layers of the planet are chemically and physically uniform where the atmosphere loses its meaning.

The theory which suggests a uniform composition, of course, does not agree with this concept. The mass, radius, and moment of inertia of Jupiter (and Saturn) indicate a low density of the planetary matter, that is, either /38
a predominantly hydrogen composition (with helium admixture) or a high temperature in its interior, so that the elasticity of the gases successfully resists hydrostatic pressure. Here considerable convection may take place as well as an energy transport of heat to the outside, which is confirmed by observation only to a small degree.

Another group of incomprehensible phenomena on Jupiter involves, on the other hand, its surface regions. As was said above, the brightness temperature of Jupiter at wavelengths of $\lambda < 3$ cm corresponds to the temperature measured in the infrared region. Already at a wavelength of $\lambda = 10.3$ cm the emission from Jupiter corresponds to a temperature of about 600° K; at $\lambda = 22$ cm, 3000° K; at $\lambda = 31$ cm, 5500° K; and at $\lambda = 68$ cm, 70,000° K; that is, these emissions are clearly of nonthermal origin and indicate the existence near Jupiter of a powerful magnetic field (many times stronger than the magnetic field of the Earth) and a belt of high-energy particles, similar to the radiation belt of the Earth. These particles move in the trap of the magnetic field and are de-excited by the mechanism of synchrotron radiation. The decimeter radio emission from Jupiter is partially polarized, which makes it possible to establish the direction of the planet's magnetic axis, that is inclined from the axis of rotation by 10°. The polarization plane varies slightly with the period, equal to the period of rotation of Jupiter, and this reveals a misalignment of the axes.

As mentioned earlier, the rotation period of Jupiter is not uniform for objects of the equatorial and the middle zones. For these, we must introduce

two systems of computing the longitudes: System I with a rotation period of $9^h50^m30^s$. 003 and System II with a period of $9^h55^m40^s$.632. The fluctuations in the polarization plane of the decimeter emission from Jupiter take place at a period of $9^h55^m29^s$.37, that is, 11 seconds shorter than the rotation period of System II, which pertains to the middle latitudes. System III for computing the longitudes is determined in this way.

The dimensions of the region of radio emission from Jupiter at decimeter wavelengths exceed its optical dimensions by far, reaching 2-3 planetary radii at the equatorial zone, although traces of this radiation may be noted also at a distance up to six radii. It is mainly this picture which serves as the basis for explaining the nonthermal emission from Jupiter by processes in the radiation belt. In the decimeter band, Jupiter is one of the most powerful sources of radio emission in the sky.

But in the decameter band ($\lambda > 7$ m), Jupiter gives powerful bursts /39
originating from discrete sources, also rotating with the period of System III. These bursts, 1-2 sec in duration or very short and on the order of 0.3 sec, have been known to radio physicists for some time, but only in 1955 were they linked to Jupiter. Even the Sun does not give such powerful impulses at decameter wavelengths. The dimensions of the sources, established interferometrically, are 10-15 or 30-40,000 km, but apparently this value is strongly exaggerated by the scattering of radio waves in interplanetary space. It is remarkable that the decameter radiation from Jupiter depends on the position of the planet's magnetic axis relative to the observer from Earth; it is strongest when the northern magnetic band passes through the central meridian. It is even more remarkable that this radiation depends on the position of the nearest of the Galilean satellites of Jupiter — Io: its intensity is maximal when the longitude of Io, computed from the superior geocentric conjunction, is equal to 90° or 240°. Jupiter's magnetosphere extends up to Io's orbit. Does Io affect the magnetosphere by a hypothetical magnetic tail or is it purely gravitational? This remains unclear. The source of decameter emission probably is different from the decimeter

emission. Just as in the case of bursts of radio emission from the Sun, the cause may lie in the plasma oscillations. But this is only a hypothesis.

Thus, the radio emission, originating from the outermost layers of Jupiter's atmosphere, does not depend on the rotation of the visible cloud surface of the planet. But it is created in the magnetosphere, which is determined by the material carrier of the planet's magnetic field, connected with the body of the planet and with its inner regions. Perhaps the rotation period of System III is the true rotation period of the planet, and the rotation of Systems I and II reflects certain systematic motions of the gas mantle of Jupiter: for latitudes greater than 12°, at a velocity of 4 m/sec, and at the equator, up to 110 m/sec.

After Jupiter, Saturn's atmosphere presents nothing new. The chemical composition is the same, only the presence of ammonia is uncertain. This is /40 easy to understand since ammonia must be in the solid state at the lower temperature of Saturn. The temperatures of Saturn measured in the infrared band vary in a range from 85 to 125° K. The lower values are preferred, since they are confirmed by radio measurements: 97° K at λ = 3.2 mm, and from 96 to 116° K at λ = 8.6 mm. With increase in wavelength, the temperature grows; 190° K at λ = 11.3 cm and about 300° K at λ = 21.3 cm. This indicates a slow elevation in temperature with depth: short-wave radiation does not reach us from the greater depths. Here there is no similarity to the sharp increase in brightness temperature which was mentioned for Jupiter and interpreted by us as synchotron radiation in the magnetosphere. We know of no indications of a magnetic field on Saturn (polarization of the radio emission is not certain).

On the disk of Saturn the details observed are much smaller than those /41 on Jupiter, probably because the clouds of Saturn consist of methane rather than of ammonia. Saturn's atmosphere is more extensive than that of Jupiter, and the differentiation in rotation velocity with latitude is stronger (10^h14^m at the equator, and 10^h40^m at a latitude of 50°).

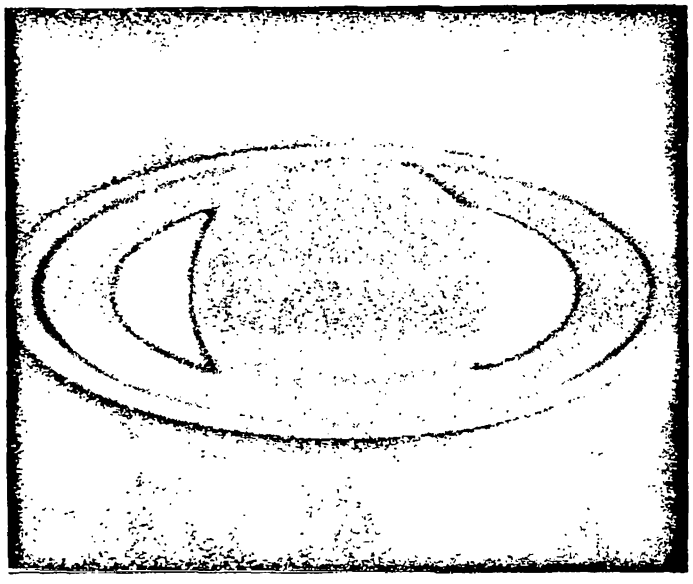

Figure 12. Photograph of Saturn and its rings.

Uranus and Neptune continue the trend mentioned in the transition from Jupiter to Saturn: intensification of the absorption bands of methane and hydrogen. But the existing quantitative estimates of the amount of methane (150 km-atm on Uranus, and 250 km-atm on Neptune) are highly unreliable and may be in error by an order of magnitude. The brightness temperature of Uranus was measured with a very high error: $T = 100° \pm 35°$ K for $\lambda = 6$ cm and $T = 128° \pm 40°$ K for $\lambda = 11.3$ cm. We do not know to which level this pertains. If the heating were only from the Sun, the equilibrium temperature would be only 60° K. It may be, just as on Jupiter, that a notable heat flux comes from the interior of the planet. Uranus and Neptune possess the highest reflectivity of any of the planets of the solar system (albedo of 0.93 and 0.84, respectively). The brightness temperature of Neptune is found from radio observations to equal $180° \pm 40°$ K at $\lambda = 1.2$ cm and $115° \pm 36°$ K at $\lambda = 3.12$ cm. Photometric observations show a temperature of 110°-130° K for sufficiently high layers of the atmosphere, and a very slow drop in density with altitude; the altitude of the uniform atmosphere is H = 50 km, which may be explained by the rich amount of hydrogen.

Pluto, the last member of our planetary system, has remained completely unstudied, but it is in no way similar to the giant planets; even its rotation is slow, with a period of 6.39 days. Its dimensions are known with a low degree of reliability, and, therefore, the low value of the albedo (0.14) derived from its visible brightness is also uncertain. If we accept this, then we must assume that Pluto's atmosphere is insignificant.

We know of 32 planetary satellites in the solar system. Their dimensions are quite different — from several kilometers (Deimos, satellite of Mars) to several thousands of kilometers (the Moon, the Galilean satellites of Jupiter, Titan — satellite of Saturn, Triton — satellite of Neptune), but only for Titan has an atmosphere of methane been reliably observed.

4. INTERNAL STRUCTURE OF THE PLANETS

The internal structure of the planets cannot be a topic for direct observations. /42 Only certain integral characteristics of a planet are functions of its internal structure, but the functional dependence is not unique, so that the investigator can only construct a guess as to a planet's structure, without pretending to have accurate knowledge. Knowledge of the temperature, density, chemical composition, and existence of phase modifications of matter as a function of depth could give a great deal of information for solving the problem of a planet's formation, be it cooling of the primitive mass ejected from the Sun or accretion by the planetary nucleus of the matter surrounding it, or condensation of matter in a constringent gas-dust cloud in the presence of the Sun. The preference for one of these three possibilities would open the way to solving still another question — the frequency of the process of forming planetary systems in the Galaxy. In addition, the question of the primary chemical composition of matter producing the solar system would be explained.

Unfortunately, we are still quite far from answering these questions. Here we can see the vast scope of theory, but not experiments.

In addition to mass, radius, and <u>mean</u> density following from it, we still know only the moment of inertia of the planet among the integral characteristics. The surface temperature in no way determines the distribution of temperature in the depths. The existence or the absence of a magnetic field on a planet would give certain indications on the internal structure of a planet if we had a reliable theory for the onset of a planet's magnetic field, even of our own Earth.

Even living on Earth, we know little about its internal structure. Concepts exist in geophysics about this that are mutually contradictory and estimates of the mean temperature differ by factors of two-three. Abrupt changes in density at the boundaries of various zones inside the Earth,

established by seismic observations, are interpreted by some authors as signs of a varying chemical composition and by others as the result of change in the phase state of matter.

But if we do not attempt to explain the details, knowledge of the mean /43
density of a planet as a whole — that is, the arithmetic result of dividing the planetary mass by its volume — results in a topic for discussion. Thus, for example, planets of the Earth group located inside the ring of asteroids, that is, Mercury, Venus, Earth, and Mars, possess a high mean density of 4-6 g/cm^3, whereas the giant planets, Jupiter, Saturn, Uranus, and Neptune, have a density significantly smaller. Jupiter and Saturn have a mean density less than the gaseous Sun. The mean density of Saturn is half that of the Sun.

One assumption stipulates that there is a substantially different chemical composition and different types of structures for certain groups of planets. The inner planets have a higher density which is naturally attributed to the presence in their interiors of iron, a heavy element which is widely distributed throughout the universe. The lower density of the giant planets can be understood if we assume their chemical composition to be near that of the Sun and the stars, where the lightest elements, hydrogen and helium, predominate.

Prior to 1920, it was assumed that Jupiter and Saturn are uncooled planets because of their low density, fast surface variability, and the existence on Jupiter of the Red Spot. They were considered as a peculiar type of small sun, not so hot as the Sun, but nevertheless, in the "fire-liquid" phase. Therefore, publication of the results of the first measurements of the thermal fluxes from these planets, indicating a very low temperature, came as a shock. Theory helped recover from the shock. Namely, the theoretical discussions did not include such small (in comparison with the Sun) bodies in the self-luminous category, since at a high surface temperature they would have to "burn up" their small reserves of heat in a short period. Then they were assumed to all be completely cold bodies. This also was

inaccurate. Let us recall that the temperature measurements of Venus in the infrared band gave a value of 240° K, and in the decimeter wavelengths it indicates a temperature of up to 700° K. The first value refers to the upper atmosphere, the upper boundary of the clouds, and the second to the planet's surface. Between one and the other level, the temperature drops in a regular fashion as a result of the fact that absorption of its thermal /44
emission takes place in the planet's atmosphere. In the cloud layer there is also a strong scattering. The atmosphere itself is sufficiently extensive to accommodate the processes of damping of the outgoing radiation.

The same factors must operate also in the huge atmospheres of the outer planets, Jupiter, Saturn, Uranus, and Neptune, so that in their depths the temperatures must reach thousands of degrees. We have seen signs of internal heat outflow from these planets, first of all in that the temperature measured in them is higher than equilibrium temperature, and secondly, during the measurements at the longer waves of the radio band the observed temperature was higher.

Another integral characteristic of the planet, its moment of inertia, is determined from the motion of the line of nodes or the line of apsides[6] of the orbits of the satellites or from the flattening of the planet if the planet is in hydrostatic equilibrium. The theory has been well developed only for slow rotation. The ratio of the moment of inertia I to the moment of inertia $^2/_3 \mathfrak{M}R^2$ of an equally large globe, the entire mass of which is distributed along the surface, is equal to 3/5 for a uniform sphere, and to zero for a body with a mass concentrated at the center. On Earth and Mars, the ratio $I:(^2/_3 \mathfrak{M}R^2)$ is equal to 0.50 and 0.58, respectively, thus indicating a sufficiently high uniformity, and for the outer planets it is shifted

[6] The line of nodes is the line of intersection of the orbital plane of the satellite with the orbital plane of the planet itself around the Sun or (in the case of artificial satellites) with the equatorial plane of the planet. The line of apsides is the major axis of the orbital ellipse, connecting the nearest and the farthest position of the satellite relative to the planet.

toward 0.39-0.31, that is, toward a greater heterogeneity. The theory which takes into account the rapid rotation of Jupiter and Saturn indicates large mean densities of 2.7 and 1.7, respectively. The purely hydrogen-helium composition of these planets would not be allowable if it had not been for the discovery (theoretically) of a metallic modification of hydrogen at a pressure of 5,000,000 atm. At 30,000,000 atmospheres, the density of hydrogen equals 3.1 g/cm^3, and of helium — 7.6 g/cm^3.

For these two planets, acceptable models are found with a relative amount of hydrogen of 80 and 68%. The models which agree with the observed /45
values of I have been found for Jupiter and Saturn also, with a hydrogen content of 78 and 63%, respectively. At the center of these planets, where the theoretically computed density reaches 31 g/cm^3 and 16 g/cm^3, helium sharply predominates.

We have cited these low-reliability numerical characteristics in order that we might give some idea as to what the internal structure of the giant planets may be; this is derived on the basis of a comparatively simple theory. Even for Uranus and Neptune, which have a comparatively high mean density of 1.47 and 1.88, respectively (versus 1.30 and 0.71 for Jupiter and Saturn), with relatively small dimensions, the hydrogen-helium composition does not fit. We must introduce into the examination the ice of water, methane, ammonia, hydrogen sulfide, oxides of metals and even metals. But by varying their content, we can obtain all the integral characteristics.

It would be very important to know how far the atmosphere of Jupiter and Saturn extends, if a liquid layer exists at the bottom of the atmosphere, or if the atmosphere and the solid surface come into contact. The theory assumes that both atmospheres are quite extensive, and comprise, respectively, 20 and 50% of the mass of the entire planet. Then at their bases there must be such high pressures that a liquid phase is impossible.

Furthermore, as we have seen in the previous chapter, Jupiter and, to a lesser degree, Saturn, have large heterogeneities under the cloud layer;

otherwise we would not observe the diversity in forms of the cloud surface of these planets. We can, therefore, pose the question as to the internal activity of Jupiter and Saturn, similar to the manner in which we pose the question of solar activity.

The inner planets, of course, are more complex to comprehend. Although it is easier to make an analogy with Earth here, the indeterminancy of the answer is not diminished, and, in particular, it remains debatable as to whether one or another planet possesses a core. One of the most popular theories of the Earth's magnetism relates the existence of a magnetic field with the dynamo mechanism in a liquid conducting core where convection takes place. At the present time, the direct contacts of the unmanned space stations with the Moon, Venus, and Mars have shown that none of these celestial bodies has any notable magnetic field.

The existence of a radiation belt on Jupiter proves the existence of a /46
magnetic field on it. As we have seen above, Saturn has no clear indications of a radiation belt. Nothing is known about this on Uranus and Neptune. Thus, of all the planets of the solar system, only on Earth and Jupiter can we state with confidence that a magnetic field exists and possibly only on these two planets are there liquid cores. We cannot exclude the possibility that Jupiter has a magnetic, productive core which reaches the atmosphere and that certain of its atmospheric formations, such as the Red Spot, have a connection with the magnetosphere.

The difficulties entailed in a theoretical investigation of the internal structure of the planets follow not only from the poor knowledge (or lack of knowledge) of the phase states of the various materials at high pressures or temperatures of several thousands of degrees — which are, apparently, typical for the interiors of the planets — but also from the incompleteness of our concepts concerning the transport of heat inside the planet. Thus, assuming that in the formation of the planet radioactive decay heated the interior of Jupiter, we can find a temperature differential of 10,000° between its center and surface, if the mechanism of thermal conductivity

operates. It is much smaller if, to the thermal conductivity, we add transport by conduction and radiation. But the theory of radiation transport inside a planet has not been completely developed.

The appropriateness of one or another model of the internal structure of a planet is examined not only from its integral characteristics, but also from the agreement of the model with our concepts concerning the past history of the planet, and this in turn depends on the way in which the solar system was formed. At the present time, it is most probable that the planets were formed by condensation of matter from a gas-dust cloud, separately into a central star and separately into planets. Before the large planets were formed, small bodies — planetesimals — were formed, which were then combined into larger ones. Here the kinetic energy, due to inelastic collisions was converted into thermal energy. The newly formed planet was warmed up. Radioactive decay was another source of internal heat, which was no less if no more effective. The planetary matter was converted from the crystal state either into a melted state if the high pressure did not prevent this or, remaining solid, changed into another modification. At /47
sufficient pressure, it was metallized, that is, under the influence of pressure the bound electrons of the atoms and molecules passed into the zone of conductivity, and this substantially increased the thermal conductivity of the matter. But increase in thermal conductivity increases the transport of heat from the depths of the planet to the outside. If these materials, for example, silicates, are not metallized and remain crystalline, then their thermal conductivity drops with elevation in temperature, thus facilitating heating of the planet. In addition to the conductivity, the heat is transported by the silicates via radiative transport.

As we see, the picture is rather complex, and if we do not wish to end in a controversy, all the above processes must agree with our concepts on the age of the solar system. Judging from the age of the Earth, the formation of the solar system took place about six billion years ago and already during the first 200 million years the planets were heated approximately as in our time. Their further thermal history is determined by the

radioactive decay of their matter. The mass of the planet determines the content of radioactive materials in absolute numbers.

On Earth only silicate rocks possess radioactivity; they are more abundant in the crust than in the mantle. Rocks containing iron are free of radioactivity. In the giant planets with their overwhelming amount of light elements, the radioactivity is weak, but the reserves of heat, accumulated in the formation of the planet (due to the energy potential) are so high that for the entire time of their existence — for example, Jupiter — the internal temperature has been lowered by no more than 1000° K.

We might think that the planets of the Earth group have an internal structure similar to that of the Earth. We assume its crust has a thickness of 18-20 km with a mean density of about 2.5 g/cm^3. Beneath it is the mantle, in which the density increases with depth, first rapidly and then slowly. The core is even deeper.

The physical heterogeneity of the Earth's structure is indicated by its elastic properties as they appear from the propagation of seismic waves. At a depth of more than 2900 km, no transverse elastic oscillations are propagated, and a sudden change takes place in the properties with increase in density. This change can be attributed to change in the chemical composi- /48
tion, for example, to the fact that the heavier elements are ejected through the viscous magma of the mantle nearer the center where they accumulate, forming a heavy core. But it is possible, using the concept of the uniformity of the Earth's chemical composition, to explain the abrupt change in elastic properties and density by the conversion of olivine rocks (a mixture of magnesium and iron orthosilicates) under the influence of high pressure from the ordinary crystalline phase state into a metallized state. This transition changes the olivine into a liquid state of high density, characteristic of the Earth's core, in which about one third of the Earth's mass is contained. But at the very center there is still another core in which about 8% of the core's mass is located, or altogether only 2% of the Earth's mass. This core consists of iron and nickel. It is solid, unlike the larger core.

Thus, the Earth, used as an example, has a multilayer structure, which may or may not be applicable for explaining the structure of the other planets of the Earth group.

Mercury, with its small mass, has the greatest density in the solar system. In it is either a small iron core, surrounded by silicates with an iron inclusion, or iron and nickel are distributed everywhere with the silicates. But they are not molten due to the sparsity of radioactive elements. For the last two billion years, Mercury has been cooling off.

Venus, which is similar to the Earth in mass and dimensions, certainly has an iron core and a core of metallized silicates. The latter contains about one fourth of the entire mass of the planet. At its boundary a pressure of 1.5 million atmospheres is reached, which makes metallization possible. The core may be molten, but a crust is located only at the surface.

Finally, Mars, probably has a small iron core (7% of the mass) and a very thin crust.

The specific difficulty in constructing models of the inner planets lies in the impossibility of controlling the (other than the Earth) magnitude of their moment of inertia. For Venus and Mercury, which have no satellites and with practically a spherical shape, which is natural with a very slow rotation, the moment of inertia cannot be determined. A flattening is observed on Mars which significantly exceeds the theoretically expected value /49 from the most widely accepted assumptions on the distribution of masses. It may be that the observations of the shape of Mars' disk involve some systematic error. In passing, we should mention that the flattening of the Earth also is greater than that which would be expected from its rotation velocity, if our planet were in hydrostatic equilibrium.

Directly related to this subject of the internal structure of the planets of the Earth group is the question of the formation of their surfaces. We have already mentioned this at the beginning, in connection with the

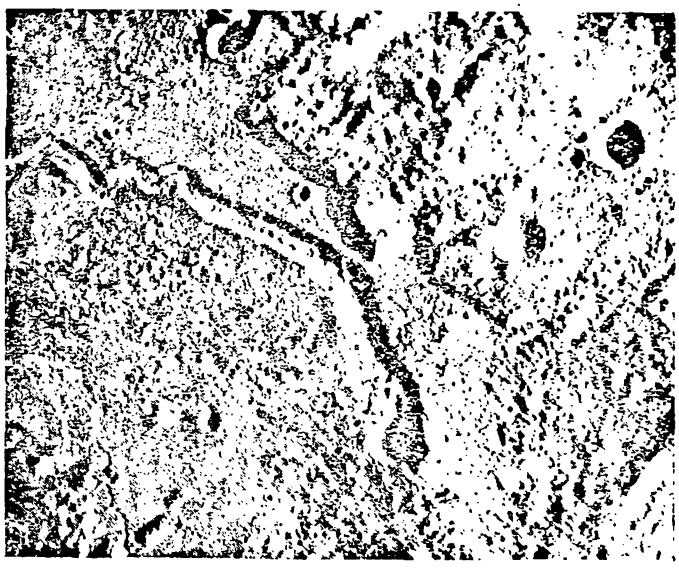

Figure 13. Rills on the Moon. The so-called "Cobra's Head" in Schröter's Valley. The picture was taken by the apparatus on the Lunar Orbiter. Frame size 4 x 4 km.

description of the lunar and Martian landscapes; only for these two objects is the landscape known to us sufficiently well. We have also turned our attention to the fact that in the formation of the lunar surface both internal and external factors played a role. If in the majority of cases it is necessary to assume an external impact of large outside masses for the formation of the /50 circular mountains, then for the formation of mountain ranges on the moon, tectonic processes are essential that are associated with the elastic tension in the crust, and the lunar seas appear as the result of lava eruptions on a huge scale. Is there a basis for assuming molten rock on the Moon, tectonic movements based on the thermal processes in the crust, and volcanic processes of small and large scale?

This last question sounds somewhat rhetorical after N. A. Kozyrev observed, if not direct volcanic damage, then an abundant generation of gases accompanying the damage inside the lunar crater Alphonsus. But what does the theory of the internal structure of the planets say on this score?

We know the mass, radius and moments of inertia of the Moon with respect to the different axes, sufficiently well to construct a model of the Moon with confidence. The lunar mass is extremely small, and, therefore, the pressure at its depths nowhere reaches such values that metallization of the silicates could take place, so that the Moon has no core. The lunar mantle contains a sufficient amount of radioactive elements which heat it up before

melting, which takes place at a depth of about 300-400 km. In any case radio measurements at various wavelengths of the heat flux leaving the Moon clearly indicate a rather rapid increase in temperature with depth, caused probably by a high concentration (four times higher than on Earth) of radioactive elements near the lunar surface.

Individual sites of the lunar surface are found to be much hotter than their surroundings. For example, such are the numerous craters and cirques of large and small dimensions such as Tycho, Copernicus, Kepler, Mösting C, and several of the seas such as Mare Tranquillitatis, Mare Serenitatis, Mare Humorum, which appear especially in relief under infrared observations during total lunar eclipses. These "hot points" can be easily explained by the fact that they are composed of rocks with high thermal conductivity, which easily transport the internal heat to the lunar surface. But this may also be heat which is accumulated by the upper surface layers during the long lunar day. On the other hand, recently a formation was detected which extended into a long band along the western boundary of Mare Humorum (toward the south from the crater Gassendi), which is constantly hotter than the surrounding sites outside the eclipse, at the height of the lunar day. Here we encounter a /51 nonequilibrium process, the cause of which is the real transport of heat along paths created by the structure of the lunar crust at a given site (fractures, faults...).

Thus, theory and observation fully indicate the existence on the Moon of high-temperature zones capable of producing tectonic processes and volcanic phenomena, and in the same manner help us understand the processes which take place on the surface of the Moon and to understand how the various details of the lunar landscape were formed. An interesting and important discovery in this respect in recent years was the discovery beneath the lunar seas of heavy masses, called mass-concentrations. The mass-concentrations were found to be anomalies in the motion of the artificial lunar satellites. They are rather numerous, but exist only beneath the seas, having a regular shape. We might think that these are residues of especially large planetesimals which pierced the crust of the Moon when they fell and produced vast

lava eruptions. The masses of the mass-concentrations comprise 10^{-5}-10^{-6} of the lunar mass.

Other explanations also exist for the mass-concentrations, for example, as formations of hardened lava of high density which, after impact of the planetesimals, were extruded upward and formed huge formations, heavier than the surrounding continental rocks. Due to its large specific weight, such a formation even with a smaller expanse in depth is capable of rendering the same pressure on the upper boundary of the plastic mantle as the more extensive, but lighter continental and subcontinental formations. (Herein, as we know, lies the hypothesis of isostasy first expressed with respect to the Earth more than 100 years ago). In this explanation there is no need to attribute to the impacted planetesimal an excessively high density, which is only slightly probable since planetesimals of iron-nickel composition could hardly ever have existed. No matter what the case may be, the existence of large heavy heterogeneities under the surface of the Moon indicates that the Moon possesses a sufficiently thick crust above the magnetic mantle.

The completely external formation — the rings of Saturn — we shall examine in the chapter on the internal structure of planets, because it has nothing in common in its nature with the surface of Saturn or its atmosphere. /52 On the contrary, it may be explained as a relict phenomenon, indicating the initial conditions which accompanied the formation of the planets four to six billions years ago.

From the time, more than 100 years ago, when Maxwell theoretically showed that the rings of Saturn cannot be integral, solid formations, and Belopol'skiy proved this experimentally by spectral observations, there has been no lack of explanations for the nature of the rings, mainly on the basis of their photometric study, during a change in the position of the rings relative to the Earth and the Sun. It was established that in the reflection of solar light the most important role is played by the mutual eclipse of the individual blocks comprising the rings. But what are the dimensions of these blocks? Unfortunately, the opinions of theorists

disagreed, and even now some cite proofs that the rings consist of fine particles with dimensions in microns, whereas others speak of a conglomerate of blocks, up to two meters in cross section and smaller fragments (on the order of centimeters and less). Probably the truth lies with the latter. As far as the thickness of the rings is concerned, it can hardly exceed 3 km, since from the myriad of "satellites" of Saturn forming the rings, only those have been left intact which moved in the equatorial plane of the planet.

It is very difficult to establish the chemical composition of the blocks. The spectrum of the rings in the infrared band reveals, as in the Martian polar cap, absorption bands that are characteristic of ice or hoarfrost. As to whether ice is found only on the surface of the blocks, or the blocks as a whole consist of ice, as yet is unknown.

5. INVESTIGATION PROCEDURES AND POINTS OF APPLICATION

Radar observation of the planets. Among the investigation methods and /53
their practical utilization, the richest possibilities are afforded by radar if it can be used effectively with respect to Jupiter and at the distance of this planet have a resolving power of even 1000 km, which corresponds to about 1/3 second of arc. At the decameter wavelengths, a mirror (or complex group of components) would be required for this with a diameter greater than 10,000 km! In the centimeter band the necessary dimensions of the mirror would be 10^3 times smaller, that is, 10 km (at a wavelength of λ = 1.7 cm). The effective wavelength might be decreased another factor of 10, and then the dimensions of the mirror would become realistic. But the problem of radar in the future will consist of analyzing the planetary surfaces with the aid of radio waves where optical means cannot penetrate the atmosphere of a planet and its clouds. For this, the millimeter waves are not suitable, since they are absorbed in the majority of planetary atmospheres and especially in water vapors. The decimeter waves apparently encounter a barrier in the ionospheres of the planets if these latter are sufficiently dense and it is these which must undoubtedly be used for scanning Jupiter.

Fortunately, contemporary powerful computer technology permits increasing the resolving power of our telescopes without resorting to huge mirrors, but by using an ingenious combination of mirrors of smaller dimensions and mathematical analysis of the incoming radio signal. It is true that the quality of the impulse returning after reflection is decreased (signal to noise ratio) but the information obtained is, nevertheless, quite substantial. An example is the reproduction shown on Figure 8 of the radar photograph of the region of the region of the Moon around the crater Tycho. It was obtained with the aid of a mirror having a diameter of 37 m at a wavelength of 3.8 cm, by Lincoln Laboratory in the USA. It shows the reflectivity of the lunar surface with a resolution of about 1 km. In order to obtain a resolution with one antenna, a mirror with a diameter of 18 km would be required!

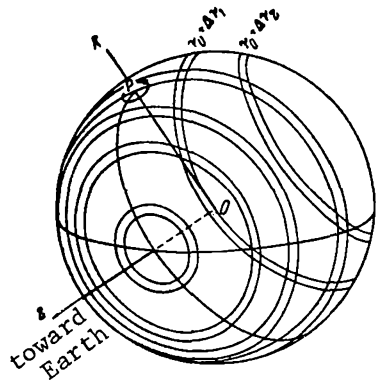

Figure 14. Schematic of radar probe of a planet (see text).

The radar method of studying the surface of planets and their rotation takes advantage of the fact that the impulse reflected from the planet carries in itself information of three /54 types: geometric (concerning distance), kinematic (concerning the approach or recession velocity), and physical (concerning the reflectivity of the site of reflection). The first type is manifested in the time of arrival of the reflected signal, the second — in the frequency of reflection of the signal, or more precisely, by the frequency shift relative to the transmitted signal, and the third — in the strength of the returned signal. Turning to Figure 14, we can see that circles on the sphere of the planet, having as a common center that point of the planet (subradar point), for which the Earth is located at zenith, are the geometric locus of the same lag in the reflected impulse. Let us select the plane XOZ, comprising the axis of rotation of the planet OX and the direction to the Earth OZ. Then the intersection of the surface of the planet with the plane parallel to the plane XOZ will be the geometric locus of the points having the same projection of velocity along the line of sight OZ during rotation of the planet. According to the Doppler-Fizeau principle, it gives the same frequency shift of the reflected signal with respect to the frequency of the signal sent. If we expand the reflected signal according to frequency (under the condition that the transmitted impulse is strictly monochromatic), then this will be equivalent to scanning the disk of the planet with a narrow slit. The intensity of the signal with a given deviation $\Delta\nu$ from the frequency ν_0 of the transmitted signal characterizes the amount /55 of energy reflected in a given band expressed on the disk by the "interval of frequencies" $\Delta\nu_1$, $\Delta\nu_2$,... (see Figure 14). With a combined analysis of the frequency shift and the lag time of the reflected signal, we can even localize those sites on the planet's disk where an increased or diminished intensity

of reflection is observed, although it is true in the general case that the solution is ambiguous.

At first glance, it seems that in the kinematic phenomena observed by the Doppler shift, nothing changes if the figure of the planet rotates with its axis of rotation around the line of sight on Figure 14. Such, in fact, is the case in observing the rotation of stars. We cannot determine the position of the axis of rotation of a star on the plane of a figure, perpendicular to the line of sight, because the position of the terrestrial observer relative to the star remains practically constant (in the framework of the annual parallax of the star). A planet is another matter. The terrestrial observer with his radar equipment continuously changes his position relative to the axis of rotation of the planet, and the observed rotation is the sum of the axial and orbital rotations of the Earth and the planet. All these motions are known in advance, other than the axial rotation, and may be taken into account in advance. But since their sum vector constantly changes its position in space relative to the vector of axial rotation of the planet, the position of the latter may be derived from observations if they are continued for a sufficiently long period of time.

The next example, pertaining to astronomers, will explain the matter. It is known that in opposition the upper planet moves with a retrograde motion most rapidly. Thus, Mars, observed from the Earth, moves during this time on a background of stars in the direction of diurnal rotation of the celestial arc. For the observer on Mars, during this time, Earth would seem to be rotating the most rapidly, and if the direction of the Earth's rotation were retrograde, during the time of the opposition of Mars, it would appear to the Martian observer to be the slowest. But this situation is fully reproducible also for the Earth observer when he observes Venus during the time of its inferior conjunction. Radar observations have shown that the width of the signal reflected by Venus is lowest in frequency rather than greatest at the moment of inferior conjunction. Hence, it follows that the /56
rotation of Venus is retrograde, and the width of the signal gives a linear

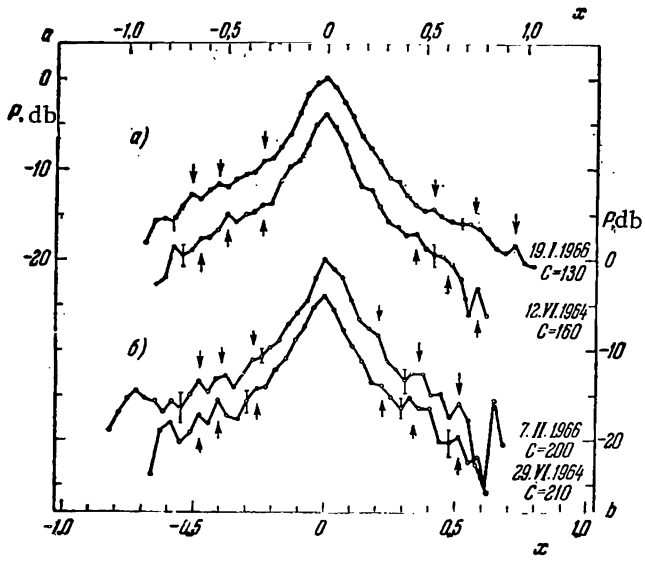

Figure 15. Comparison of profiles of radar signals reflected from Venus at a wavelength of 39 cm in two inferior conjunctions of the planet in January-February 1966 and in June 1964. The repetition of details with respect to their reflectivity can be seen.

rotation velocity for Venus at the equator, whence the period of rotation is derived. Finally, the law governing the change in the signal width with time establishes the orientation of the axis of rotation in space.

The rotation period of Venus is most precisely derived by comparing the relationship of the frequency profiles of the reflected signals during the times of the different inferior conjunctions. One or another detail of this profile is repeated during the time of subsequent conjunctions. Its appearance at one and the same place of the profile indicates that a complete number of synodic (that is, relative to the Earth) periods of rotation of Venus has taken place. The transition from the synodic period S to the stellar period P is given by the formula cited (for circular orbits) by Copernicus: /57

$$\frac{1}{E} + \frac{1}{P} = \frac{1}{S},$$

where E is the period of rotation of the Earth around the Sun. If the rotation of Venus were forward, then a minus sign would be placed in front of 1/P. It is natural that S must be taken in absolute value.

The signal transmitted by radar has circular polarization. After specular reflection from sufficiently large details on the surface of a planet, it returns to Earth still polarized in the same manner, but opposed to the direction of rotation. A sufficiently rough landscape makes possible a specular reflection even from those places on the planet's disk which are

distant from the center all the way up to the limb itself. On the other hand, the planet with a smooth surface gives a polarized reflection only from the central parts of the disk. Its effective cross section is greatly reduced, and for radar probes of the planet a more powerful impulse must be used.

If the reflecting surface has numerous irregularities, the radius of curvature of which is less than the wavelength of the incident signal, polarizations in the inverse direction do not set in, and the reflected signal retains the direction of the circular polarization of the incident signal. This part of the reflected signal is called its depolarized component, which may be the subject of a special investigation when the signal arrives at the receiving antenna. In summation, radar permits investigating separately the polarized and unpolarized components of the reflected radiation, and from this the structure of the planet's surface can be judged. The coefficient of reflection during normal incidence makes it possible to find the dielectric constant of the surface materials, that is, their physical characteristics.

Let us note finally that the possible rotation of the plane of polarization during the propagation of radar impulses permits investigating the electrical state of the interplanetary and circumplanetary plasma, and also the magnetic field around the planet on the basis of the Faraday effect.

Thus, the greatest information is contained in radar-reflected signals, which allows us to discover many facts that had previously been inaccessible. Earlier we mentioned a number of such facts about Venus, which is covered /58
with a dense cloud layer. The large amount of information reflects the scope of the investigation method.

Radar gives the hope of collecting the most valuable information on the surface of Jupiter, to establish whether the surface adjacent to the atmosphere is solid or liquid, to find the period of rotation of this surface, the degree of its geometric and physical heterogeneity, the relationship

between the surface and cloud formations, and many other facts which have been difficult to predict.

But we encounter one basic difficulty in this approach, that is, the inadequate strength of the signal and the insufficient area of the antenna for sending and receiving the signal in the case of such a remote object as Jupiter, or such a small one as Mercury. The strength of the reflected signal, received by the antenna, is inversely proportional to the fourth power of the distance to the planet, and directly proportional only to the first power of the strength of the transmitted signal. The signal is damped in proportion to the square of the distance in the outgoing and incoming leg. Although, when the irradiator is placed at the focal point of the parabolic mirror, the beam of radio waves transmitted by the antenna must be parallel, diffraction makes it divergent within the limits of the angle of the directional diagram, which is always found to be greater than the angular diameter of the planet's disk. If the cross section increases in proportion to the square of the distance and becomes greater than its dimensions near the planet, then part of it will be wasted for the experiment. Therefore, the effectiveness of the radar experiment is higher, the narrower the directional diagram, and, therefore, is proportional to the square of the mirror's diameter. But this same mirror is in operation during the reception of the reflected signal, so that the success of the radar probe of the planets is defined as the fourth power of the diameter of the mirror. From Figure 16, which shows how many times the strength of the signal is attenuated travelling back and forth, it is clear that even the radar probe of Jupiter, if we expect reliable results from it, will require amplifying the strength of the transmitted impulse and increasing the dimensions of the antenna. In fact, at the present time the only fully reliable data, except for the Moon, are those of the inner planets, mainly Venus, and with the greatest success in the upper interval indicated on Figure 16. The difficulties of radar scanning of Mercury have also been successfully overcome. /59 For the last two oppositions, Mars has also become an obedient subject for radar investigations. Jupiter requires improvement and intensification of technology. Although the data concerning its radar scanning have been

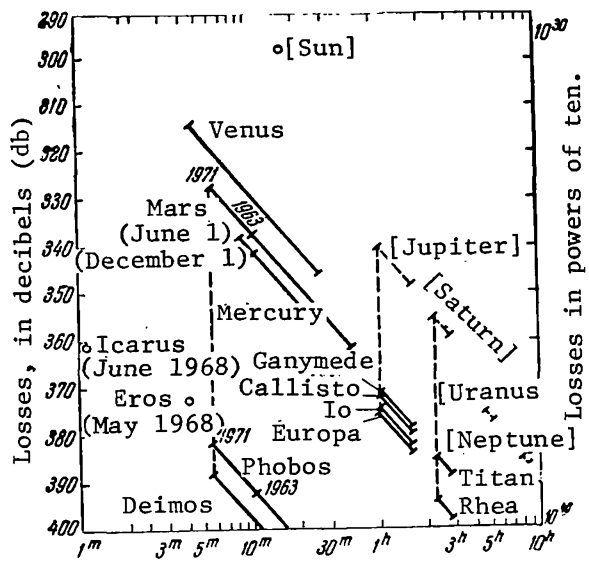

Figure 16. Attenuation of signal strength during its return to the radar equipment. Along the abscissa is plotted the time of the signal's motion at both ends, and along the ordinate is plotted, on the right, the attenuations in powers of ten, and on the left, in decibels. Each space object is represented by a line, encompassing the entire distance of the object from the Earth — from the nearest to the remotest.

published in print, they have not been confirmed. Up to the present time, the growth in sensitivity of radar devices on Earth has been at a rate of 5.5 dB (or 3.5 times) a year. It may be that a threshold corresponding to a loss of 390 db. will be reached in 1972. Then it will be possible to have accurate radar scanning of Jupiter and even its satellites. Radar scanning of Saturn will also be possible.

Spectroscopy of the planets. Great possibilities for spectral /60 analysis of the planetary atmospheres are revealed by the method of Fourier-spectroscopy. The principles involved in this method can be understood if we recall the operating principles of the Michelson interferometer (Figure 17). Light from the point source S with the aid of the collimator lens L_1 travels in a parallel beam to the separating plate P, mounted at an angle of 45°. Here the beam is split, being reflected from the translucent reflecting plane of the plate P, and partially travelling through it. The first beam encounters the mirror M_1, and the second — the mirror M_2. Reflected from them, the light again encounters the plate P, being partially reflected from it, and partially passing through it, after which it is directed toward the lens L_2, which gathers both beams at the focal point F, where there may be an eye, a photoplate or a photomultiplier. The beams travelling toward L_2 interfere with one another. The focal point F will be "light" or "dark" depending on

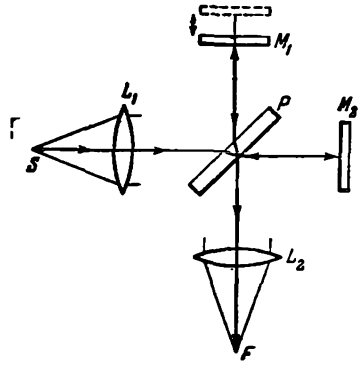

Figure 17. Schematic of the Michelson interferometer.

whether the path difference of the beams forms an even or odd number of half-waves of monochromatic light of a given wavelength. If the light is not monochromatic, but "white", then it will always contain a wavelength λ', which will give "light", and along with it λ'', which will result in a "dark" point λ' and λ'' will differ to a lesser extent, the greater the path difference of the beams, reflected from M_1 and M_2, because with a large path difference (due to the large number of half-waves contained in it) even for λ' and λ'' quite close, there may be a difference up to a half-wave(7).

Now if the mirror M_1 moves at a constant rate v from the middle position /61 (for which the path difference is equal to zero) to the path difference τ, then at the point F each wavelength will be modulated at a different frequency. The wavelength $\lambda = \tau$ will be modulated only one time, and the smallest λ_m of the wavelengths transmitted — τ/λ_m times. In the general case, since the path τ will be travelled for a time τ/v, the frequency of modulation

$$f = \tau/\lambda : \tau/v = v/\lambda$$

will also be different for the different wavelengths. At the same time the intensity of the radiation modulated at a frequency f will be a direct function of the intensity of the radiation at the wavelength $\lambda = v/f$. When the photocurrent is recorded from the photocell at the focal point F, then it expresses the effect of adding the emissions at all wavelengths of the examined interval. This would be like noise containing a vibration in the

(7) Let us say the path difference is $500\lambda'$ and then λ'' is determined from the equation $1000\frac{\lambda'}{2} = 1001\frac{\lambda''}{2}$, which gives $\lambda' - \lambda'' = 0.001\lambda''$, whereas with a path difference of $50\lambda'$, we find $\lambda' - \lambda'' = 0.01\lambda''$.

wide frequency band. But at each moment their frequencies and their wavelengths λ participate in this noise and, moreover, at a different intensity, corresponding to the intensity in the spectrum.

Since the examined noise is composed of many harmonic vibrations, all of its "vibration" for the period of the photocurrent recording (when the mirror of the interferometer moves) can be expanded into elementary harmonic functions, for example, according to cosines of all the frequencies of modulation — that is, it is subject to Fourier transformation. Such a possibility (theorists and experimenters) was predicted for optics even at the beginning of this century. But the practical mastering of this method became an actuality only in recent years after overcoming certain specific experimental difficulties, especially noticeable in astronomy, when the image of an object flickers strongly due to the instability of the atmosphere. Furthermore, the assistance of modern electronic computers has become possible, since without them the tremendous computational effort associated with Fourier transforms is simply inconceivable. It was further found that spectroscopy with the aid of an interferometer has the advantage of a greater luminosity versus the ordinary recording of the intensity of the spectrum. This is especially important in astronomy where the light sources to be investigated are very weak in comparison with those in the laboratory. With the appropriate precautions, the use of this method will significantly /62
increase the accuracy of the measurements. Finally, the resolving power in Fourier spectroscopy may be significantly higher than in the classical method[8]. This is especially apparent in the infrared band, but not because the ordinary methods give a low resolving power in the spectrum (this is not so), but because, due to the low sensitivity of the infrared light receivers, the experimeter must register a wide band of the spectrum directly. Otherwise

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[8] As we can see from the footnote on page 60, the resolution is obtained equal to $1/2\tau$ in the scale of wave numbers σ (in cm^{-1}). With the aid of the relationship $\Delta\sigma/\sigma = -\Delta\lambda/\lambda$ we find the expression $\Delta\lambda = -\lambda^2\Delta\sigma$, which shows that the resolution is improved with decrease in wavelength.

his light receiver will simply not respond to the incoming luminous flux. The use of infrared receivers, which are distinguished by the fact that their noise, as a rule, does not depend on the strength of the signal, makes Fourier spectroscopy quite advantageous, especially when the problem is to obtain a high resolution in the spectrum.

All these properties of Fourier spectroscopy are especially important in the investigation of the planets, since the majority of molecules comprising planetary atmospheres are best seen in the infrared band with its rotational-vibrational spectra.

All the small luminous fluxes reaching us from the celestial bodies including the planets, when our purpose is to carry out precise measurements of the intensity in the spectrum with a high resolving system, require a long recording time even with large telescopes and with the use of Fourier spectroscopy. Modern technical procedures — recording on punched tape or on magnetic tape and the subsequent transmission of this recording by telephone to a large computer center — make it possible with the least loss of effort and time to obtain a final result which even 15-20 years ago would have been impossible. Figure 18 shows a part of the spectrum of Venus, obtained in this manner by Konn and Mayar on July 3, 1966 on the 193-cm reflector of the observatory of Upper Province (France) in two approaches when Venus was near the meridian (Venera-1) and far from it (Venera-2). The telluric lines, formed in the Earth's atmosphere, designated by the letter T, are much stronger in the second case. For comparison the spectrum of the Sun /64 was recorded. All the lines, in the spectrum of Venus and absent in the spectrum of the Sun, belong to the weak band of carbon dioxide around λ = = 2.2 μ. The total observation time of the spectral region, which is twice as wide as shown here, was 27 hours. The time for transmitting the data to the computer center is somewhat less than this, but the computations themselves occupy 1-2 hours.

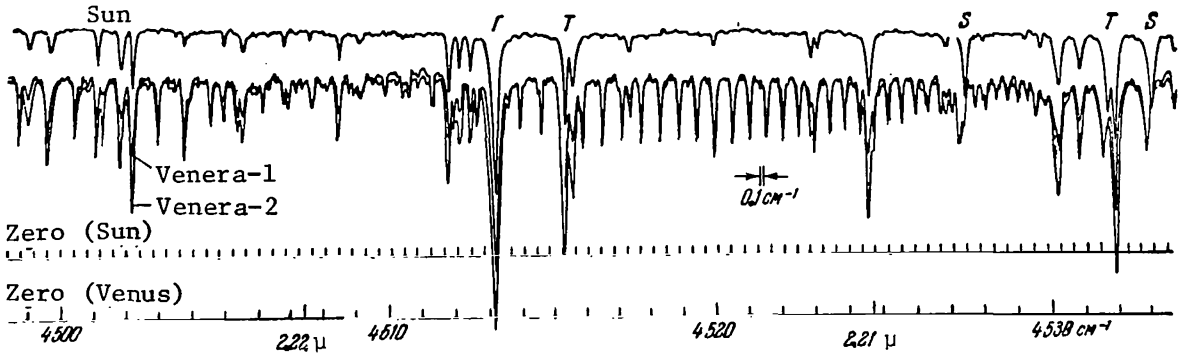

Figure 18. Part of the spectrum of Venus compared with the spectrum of the Sun in the range of 2.22-2.23 μ. The telluric lines (formed in the atmosphere of the Earth) are denoted by the letter T. The lines forming in the solar atmosphere are denoted by the letter S. The others are formed in the atmosphere of Venus. The only difference in the spectra from Venera-1 and Venera-2 is that the second was obtained at a lower position of Venus over the horizon. The majority of the lines in the spectrum of Venus belong to the weak band of carbon dioxide (CO_2).

Radioscopy of a Planet's Atmosphere. The previously mentioned radioscopy of the atmosphere of a planet by the light of a star is a phenomenon that is both unusual and difficult to observe.

This phenomenon does not depend on the will of man. Radioscopy of the atmosphere of a planet by radio waves from a spacecraft orbiting the planet is a much simpler affair (after the equipment reaches its target), and it may be organized just like any other physical experiment.

Let us acquaint ourselves with the principles of this experiment. Figure 19a, shows the passage of light beams through the atmosphere of a planet in simplified form, as though the atmosphere consisted of individual layers, at the boundary of which the light is refracted, so that the angle of refraction is less than the angle of incidence if the light travels from a less dense layer to a more dense one. The opposite picture is observed when the light travels from the atmosphere. If we were to plot the refraction on

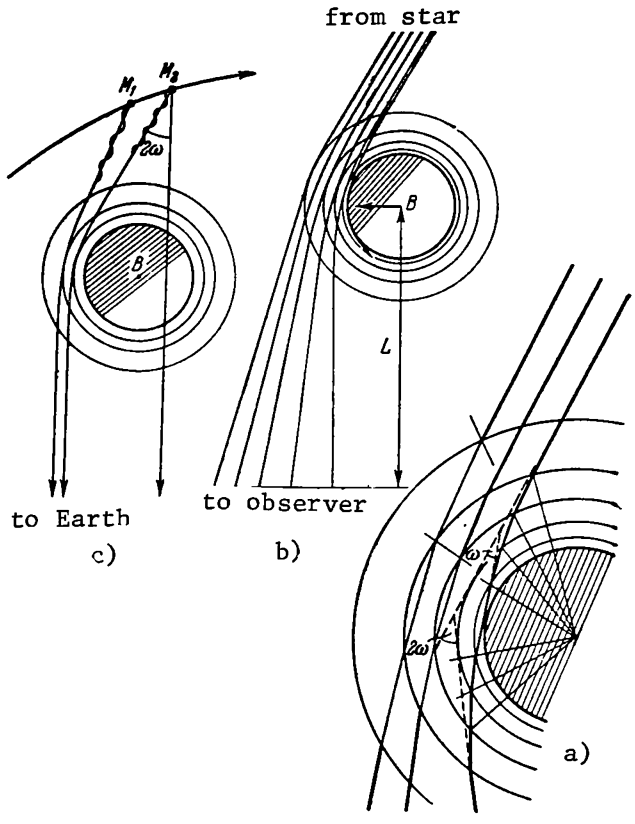

Figure 19. Schematic of the radioscopy of the atmosphere of a planet by the light of a star (b) and by radio signals from a spacecraft (c). Refraction in the atmosphere of the planet (a).

an infinitely large number of infinitely thin layers, the trajectory of the beam in the atmosphere would appear to be curvilinear in precise agreement with actuality. The described phenomenon is called <u>atmospheric refraction</u> in astronomy. As is obvious from the drawing, the initially parallel pencil of rays becomes divergent due to the refraction.

Now let us look at Figure 19b, where the obscuration of a planet by a star is shown. The planet is first affected by the star over its entire atmosphere. The parallel pencil of light from the star becomes divergent. When one of these rays, or more properly, a narrow pencil of rays, reaches the observer located at a distance L from the planet, the observer sees the star, but its brightness will be weakened, because as a result of refraction, the energy contained in the <u>divergent</u> pencil of rays is less than before refraction in the parallel beam of the same cross section. Such a <u>refraction</u> weakening is significantly greater than the weakening of /65
light by absorption in the atmosphere. At first, when the star is behind the disk of the planet, light approaches the observer which has penetrated the more rarefied layers of the atmosphere, and then the denser ones. The star "darkens and goes out". This takes place more effectively, the greater the /66
distance L of the observer from the planet. A precise formula shows that the weakening factor will be $(1 + 2\omega L\beta)$ where 2ω is the angle at which the light

ray is deflected as a result of refraction when it passes through the atmosphere of the planet (horizontally, in the lowest part of its trajectory), and β is the characteristic of change in the density of the atmosphere with altitude. An increase of altitude of $H = 1/\beta$ km results in a density drop of a factor of e. In the formula for the damping, only ω is a variable quantity, and the observer sees the progressive damping of the brightness of the star in proportion to the growth in the horizontal refraction ω. Knowing very precisely the position of the planet and the star in space, and also the radius of the planet, we can compute at any given moment of observation how near the star approaches the planet's disk, and in the same manner we may always know the angle ω. Consequently, from the observations we can determine the quantity β or its inverse scale of height H. But this quantity is associated with the characteristics of the atmosphere — its molecular weight μ, temperature T, and acceleration of the force of gravity g, by the simple formula

$$H=\frac{\Re T}{\mu g},$$

where $\Re$ is a universal gas constant. The quantity g is easy to compute. Consequently, after determining H from the observations, we can find the molecular weight μ, if we know the temperature T. Conversely, we can determine T if we know μ.

Unfortunately, the temperature T is not constant in the atmospheres of the planets, although in the upper stratospheric layers, it is rather invariable. The radii of the planets are known to us with an insufficiently high degree of accuracy, so that slight uncertainty remains in determining the level of the planet's atmosphere, to which these or other values of μ or T pertain. The divergence may reach several scores of kilometers for Venus and hundreds of kilometers for Jupiter, but for an approximate determination of the physical parameters of the planets' atmospheres the method of radioscopy is quite good.

One of its variations, radioscopy of the atmosphere by radio waves originating from a spacecraft is shown schematically on Figure 19c. It differs from the preceding case in that here we are studying the passage through the atmosphere of a beam of radio waves which diverge from the point /67 source, the position of which $M_1, M_2, \ldots$ at different moments of time is known precisely. Figure 19c shows only those rays originating from the craft in positions M_1 and M_2, which have reached the observer on Earth. It seems that here also refraction damping[9] is also taking place, but in addition, there is still another effect, that is, change in the frequency or wavelength of the radio emission when it passes through the atmosphere. In general when the spacecraft travels the trajectory $M_1, M_2, \ldots$, the frequency of the radio signal varies as a result of the Doppler effect, because the rate of motion of the spacecraft and the angle between the line of sight and the direction of the motion both change. If the rate of motion in the projection on the line of sight is v, and the propagation rate of the radio waves is c, then the relative change $\Delta\nu$ in frequency ν — that is, $\Delta\nu/\nu$ — is equal to the ratio v/c. But the rate propagation of the radio waves differs in a vacuum and in a refracting medium, whatever the atmosphere of the planet may be. Therefore, the signal may arrive on Earth with a phase which differs from that in the absence of an atmosphere. Taking into account all the sources of change in frequency and time of propagation on the path from the spacecraft to the receiving antenna (including the role of the Earth's atmosphere), we can compute for each moment the changes in the phase of the arriving signal, and after comparing them with the observed changes and after determining the divergence, we can attribute it to the effect of the planet's atmosphere. The divergence directly influences the change in the coefficient of refraction n, and this quantity — more precisely, its difference from unity, (n-1) — depends directly on the density of the atmosphere and its chemical composition. Thus, of course, after complicated treatment, we can obtain the density distribution with respect to altitude, and, hence, it is

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[9] The picture of the refraction of radio waves in the atmosphere, shown on Figure 19c, corresponds to short waves of the centimeter and decimeter bands.

easy to convert also to temperature. This method gives more precise results than measurement of the signal attenuation.

In the experiment of Mariner-4 in its orbit near Mars, phase shifts were observed in the oscillations arriving both when the craft approached the planet's disk and when it emerged from it. Quantitatively they agreed well and during the time of the approach and emergence reached about 30 complete cycles of oscillations, which converting to the quantity (n-1) comprised a factor of 3.6×10^{-6}. Hence, the value of the atmospheric density at the /68
surface of the planet is about 1.5×10^{-5} g/cm^3 (under certain assumptions concerning the chemical composition of the atmosphere) and the pressure varied between 4 and 6 millibars which is found to be in satisfactory agreement with the spectroscopic results. The scale height was found to be between 8 and 10 km. Under various assumptions on the chemical composition, the temperature is found to vary from 170 to 180° K. The transmitter giving all this information operated at a frequency of 2297 MHz and had a power of only 10 watts! Its distance from the Earth during this time was 216 million kilometers.

In the experiment with Mariner-5 which completed flight around Venus with a transmitter frequency of 2297 MHz, the phase shift reached 140 cycles, and the changes in (n-1) comprised from 15×10^{-6} to 1464×10^{-6} for distances from 6123 to 6088 km from the investigated atmospheric layer to the center of the planet. But what altitude above the level of the surface do these distances represent? For an answer to this question, we must know the radius of the planet's surface. Visual observations cannot give this quantity for Venus, — it is determined only from radio observations and more accurately, — from radar probes. Radar probes resulted in a radius of Venus between 6050 and 6056 km. Consequently, the flight of Mariner-5 gave physical characteristics of Venus' atmosphere from an altitude of 70 km to 32 km. The altitude scale was defined as 8.9 km for the lower boundary, and the values of the temperature were found to be about 400° K and a pressure of about 6 atm. The pressure and temperature pattern, obtained from this experiment, agrees excellently with the pattern of these quantities in the

experiments with the unmanned spacecraft Venera-4 and Venera-5. If it is applied up to the very lowest level of the atmosphere, with a radius of 6053 km, then figures are found that are similar to those given above, that is, a temperature of about 770° K and a pressure of about 100 atm.

In the entire experiment of Mariner-5, precise knowledge of the entire geometry of the phenomenon is of primary importance, that is, the mutual distribution of the points M_1, M_2, ..., of Venus and the Earth, and the value of the planet's radius. Change in frequencies of the signals is accomplished with great accuracy up to 0.08 Hz, which made it possible to follow with high accuracy the trajectory of the unmanned spacecraft Mariner-5 for the entire trip. In this case celestial-mechanical computations were carried out in parallel, especially when the spacecraft was nearing Venus, since Venus /69
produced a very substantial change in the orbit of the craft relative to the Sun (its velocity relative to the planet grew from 3.05 to 8.56 km/sec, and the frequency of the received signals changed by 95,000 Hz because of this). American scientists consider that, as a result of all the measurements and computations, the position of Mariner-5 relative to the center of Venus was known for the entire approach time within an error no greater than 0.2 km. But in order to obtain such high accuracy, the motion of Venus must be known as precisely as possible. The necessary data, reinforced by the results of radar observations, were given by celestial mechanics.

We should note the fact that in the radioscopy of the Martian atmosphere it is not the signal itself from Mariner that was observed, but a retranslation by it of the signal sent from Earth. This signal was regulated by the oscillations of rubidium atomic source which ensured its superhigh stability. In investigating the atmosphere of Venus, such a technique was not used, since the double passage of the signal through its superdense atmosphere threatened too large an attenuation of the signal's strength.

Greenhouse effect. The greenhouse effect of a planet's atmosphere, just as in our hothouses covered with glass, is based on the fact that solar

radiation, heating the planet's surface, passes through the atmosphere comparatively freely, and the radiation from the heated surface of the planet cannot go beyond the limits of the atmosphere, since it is absorbed by the gases which heat them. In our hothouses glass plays this role. It does not prevent the short-wave solar radiation from penetrating inside the hothouses, but it does restrain the radiation of heat from the hothouse to the outside, since this radiation is of the long-wave type, and the glass for the long-wave, infrared radiation is opaque. Not every atmosphere possesses such a restraining effect: for example, hydrogen, helium and nitrogen atmospheres do not have this property.

Quite another situation is involved with an atmosphere containing carbon dioxide, water vapors, and ozone. If we investigate the spectrum of any source, the light of which has travelled a sufficiently long path in carbon dioxide or in water vapors, then in the infrared band of the spectrum we will detect a number of very dark bands, indicating the absorption of radiation. /70 These bands give information on the radiation at a wavelength of 1-4 μ (mainly water vapors), but at 4 and 15 μ carbon dioxide, and at 6 and 50 μ — water vapors almost completely retard the radiation. A planet radiates basically between 10 and 15 μ, if its temperature equals 250° K, and between 4 and 15 μ at a temperature of 600° K. Fortunately, for astronomy, these bands do not merge with one another, if we examine the radiation of celestial bodies after passing through the Earth's atmosphere. Spectral "windows of transparency" are found in them, that is, wavelength intervals of the infrared band in which the absorption is not high, and celestial bodies can be observed without losses due to absorption.

However, the Earth's atmosphere is not rich with carbon dioxide and water vapors. Venus is a different situation, where more than 90% of the atmosphere consists of carbon dioxide, and the absolute content of water vapor is significantly higher than in the atmosphere of the Earth. Thus, all the absorption bands of these gases are merged together, and the natural heat radiation of the planet, if it has a temperature of 200-700° K, cannot exceed the limits of even the lowest layers of the atmosphere, — it will

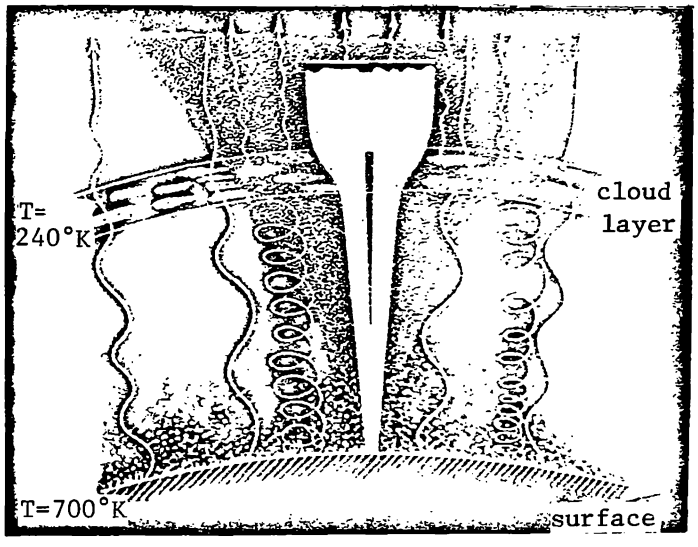

Figure 20. Greenhouse effect in the atmosphere of a planet rich with carbon dioxide and water vapors. The solar energy flux arriving at a given site on the planet is shown by the light (wedge-shaped) band. In the cloud layer a significant part of this energy is scattered, which is shown by the decrease in band width. This scattering continues farther below the clouds due to the encounter of the photons with the gas molecules and the solid and liquid particles, suspended in the atmosphere. A very small part of the radiation, which is absorbed here and heats the planet, reaches the surface of the planet. Simultaneously with scattering in the atmosphere an insignificant absorption takes place (the gray band inside the light one) thus heating the atmosphere. The heated surface of the planet emits long-wave radiation which is absorbed by the atmosphere as a whole (attenuation of the light points with altitude), with the exception of the radio waves of 3-50 cm, which leave the atmosphere without hindrance (wavy lines). Convective currents (the weak spiral lines) also leave the hot surface of the planet into the atmosphere.

be absorbed. Of course, it will be partially reradiated, but a considerable part of it will go into heating the gases, and the reradiation will go to all sides including back to the surface. As a result, the thermal radiation flux going outside is decreased almost to zero. But the heat flux leaving the Sun does not cease, the surface of the planet is heated, and only when equilibrium is established between the freely arriving heat and the natural heat, which leaves the planet "with difficulty", is there a temperature equilibrium established at a certain comparatively high level.

Figure 20 shows this with a schematic representation of the conditions of heat transport in the atmosphere of a planet, as applied specifically to Venus.

A luminous energy flux from the Sun reaches the highly positioned cloud layer of the planet. This is shown by the light shape in the center of the drawing, the width of which

corresponds to the strength of the flux. After encountering the cloud cover, the solar light is scattered by the clouds. The scattering is very great. It continues also below the clouds where the flux undergoes strong attenuation, /71 and is propagated farther down, the greater it is scattered, creating a luminous field similar to that which exists on Earth on a cloudy day (this is shown on the drawing by an overall semi-light background). Let us recall that the scattering involves the scattering of atoms, molecules, and particles reradiating the incoming photons, without changing their frequencies. The /72 situation is that the almost unchanged solar light, scattered by the clouds or penetrated from under the cloud layer, is emitted back into space by Venus, — about 75% of all the light incident on it. If we speak about all the solar energy, including the infrared and the ultraviolet bands of the spectrum, then for the planet there remains only 28%; and 72% is reflected and lost irrevocably. There 28% are absorbed, that is, they either go into restructuring the internal structure of the atoms or molecules, and then into heating the gas, or — unlike scattering — the absorbed photons are reradiated at another wavelength, but such reradiated photons are recaptured and also go into heating the gas. This process of progressive absorption is shown on Figure 20 by the tapering gray wedge shown inside the outer light wedge of the scattered energy flux reaching the surface of the planet in a negligible amount.

At the same time, the hot surface of the planet radiates a rather large amount of energy (the light points on Figure 20). The upward energy flux is very rapidly attenuated because of absorption in the carbon dioxide and water vapors. Nothing reaches the cloud layer; even convection (on Figure 20 the spiral columns) is in no position to help transport the heat. Therefore, measurements of the natural heat flux from Venus in the infrared band (after subtracting the solar energy flux reflected from the clouds) leads to a temperature of 240° K, which we attribute to the cloud layer. Only radiation through radio waves in the band from 3 cm to 50 cm reaches us unimpeded from the surface. Neither the dense atmosphere nor the clouds affect it, and, therefore, with their help the real temperature on the surface of Venus is about 700° K.

TABLES OF PHYSICAL CHARACTERISTICS OF THE MAJOR PLANETS AND THE MOON

MERCURY

Mean distance from the Sun	a	0.387 A.U.(*)
Eccentricity of orbit	e	0.206
Inclination of orbital plane to ecliptic	i	7°0'15"
Rotation period around the Sun	P	88.0 days
Synodic rotation period	S	115.9 days
Mean rate of motion in orbit	v	47.9 km/sec
Diameter from radar measurements	D_0	4860 $\pm$ 4 km
Diameter from optical measurements	D	4850 $\pm$ 40 km
Angular diameter, seen from the Earth:		
(a) when Mercury moves along the Sun's disk — in November	d"	9.8"
(a) when Mercury moves along the Sun's disk — in May	d	12.1"
(b) in mean (by distance) elongation	d	7.3"
Area of disk in average elongation	ω	$1 \cdot 10^{-9}$ sterad
Area of disk, visible from Sun at mean distance from it	Ω	$1.3 \cdot 10^{-8}$ sterad
Mass in solar masses	$\mathfrak{M}$	1:6021000
Mass in Earth masses	$\mathfrak{M}$	0.956
Absolute mass	$\mathfrak{M}$	$3.303 \cdot 10^{26}$ g
Volume in Earth volumes	V_0	0.0553
Mean density	$\bar{\rho}$	5.59 g/cm^3
Rotation period around axis (stellar days)	p'	58.65 days
Inclination of equator to orbital plane	i'	7°
Moment of inertia	unknown	
Acceleration of force of gravity at equator	g_e	372 cm/sec^2

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(*) A.U. = astronomical unit, equal to the mean distance of the Earth from the Sun; 1 A.U. = 149,600,000 kilometers.

Acceleration of force of gravity in units of Earth acceleration	g_e	0.38
Critical (parabolic) velocity at which a body leaves the planet	v_e	4.3 km/sec
Stellar magnitude during the time of the mean(by distance) superior conjunction in the V system.		$-1^m.71$
Stellar magnitude in elongation (as a function of distance from the Sun) in the V system.		from $-0^m.3$ to $+0^m.6$
Index of yellowness (excess over the color index of the Sun)		
in the system B-V		$+0^m.30$
in the system B-I		$+0^m.93$
Visual spherical albedo	A_v	0.056
Thermal spherical albedo	A_b	0.09
Equilibrium mean temperature at a mean distance from the Sun	T_{comp}	505° K
Equilibrium mean temperature for the subsolar point (computed)		618° K
From measurements in infrared rays	T	613° K
Dark side has a temperature no higher than		250° K
In the microwave region, the following mean brightness temperatures over the disk (at a mean distance from the Sun) are measured at:	T_b	
λ = 0.34 cm		200 - 220° K
0.86 cm		404 ± 40°
1.53 cm		465 ± 115°
3.5 cm		390 ± 100°
10.6 cm		290 ± 40°
11.3 cm		290 ± 40°
Dependence of T_b on phase		unconfirmed
Atmosphere		unconfirmed
The amount of CO_2 determined at the limit		from 1.5 to 3.5 m-atm

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N_2 and Ar and, in the upper layers — CO and O_2 as a result of dissociation of carbon dioxide are also theoretically possible. Mercury has no satellites.

VENUS

Mean distance from Sun	a	0.723 A.U.
Eccentricity of orbit	e	0.007
Inclination of orbital plane to plane of ecliptic	i	3°23'40"
Rotation period around Sun	P	224.7 days
Synodic rotation period	S	583.9 days
Mean rate of motion in orbit	v	35.0 km/sec
Diameter over surface	D_0	12105 ±4 km
Diameter over level of cloud layer	D	12200 ±20 km
Diameter over level of obscuration of Regulus	D'	12338 ±10 km
Angular diameter seen from the Earth		
in inferior conjunction	d	60.8" (max. 65.2")
in superior conjunction	d	9.8" (min. 9.5")
Area of disk seen from the Earth:		
in inferior conjunction	ω	$6.8 \cdot 10^{-8}$ sterads
in superior conjunction	ω	$1.8 \cdot 10^{-9}$ sterads
Area of disk seen from the Sun at a mean distance from it	Ω	$1.0 \cdot 10^{-8}$ sterads
Mass in solar masses	$\mathfrak{M}$	1.408250
Mass in Earth masses	$\mathfrak{M}$	0.815
Absolute mass	$\mathfrak{M}$	$4.867 \cdot 10^{27}$
Volume in earth masses	V_0	0.861 g
Mean density	$\bar{\rho}$	5.22 g/cm^3
Rotation period around axis (stellar days); retrograde rotation	P'	243.0 :0.5 days /75
Rotation period of visible surface (cloud layer);retrograde rotation	P"	4 days
Inclination of equator to orbital plane	t'	178° (*)
Moment of inertia	unknown	
Acceleration of force of gravity at equator	g_e	886 cm/sec^2

(*) This angle is equal to 2°, but the directions of the axial and orbital motions are opposite to one another.

Acceleration of force of gravity in units of earth acceleration	g_e'	0.90
Critical (parabolic) velocity at which a body leaves the planet	v_e	10.3 km/sec
Stellar magnitude during time of mean (by distance) superior conjunction in the system V		$-3^m.81$
Stellar magnitude during time of inferior conjunction when the planet is located precisely between the Sun and the Earth.		$-0^m.1$
The same near inferior conjunction		$-3^m.5$
Maximum brightness (before or after inferior conjunction of 35 days)		$-4^m.45$
Index of yellowness (excess over color index of Sun) in the system	B-V	$-0^m.19$
Visual spherical albedo	A_v	0.76
Thermal spherical albedo	A_b	0.77 ± 0.07
Equilibrium mean temperature (computed)	T_{comp}	229° K
Actually observable temperature of cloud layer over the disk (from infrared measurements) without confirmed difference in night and day side	T_b	225 - 235 - 240° K
Measured in the microwave region at:		
$\lambda \leq 0.3$ cm	T_b	$\sim$ 300° K
$\lambda \geq 2$ cm		$\sim$ 700° K
$\lambda \geq 21$ cm		$\leq$ 600° K
By direct measurement from unmanned spacecraft Venera-4, Venera-6, and Mariner-5 of the surface temperature	T	$\sim 750° \pm 100°$ K
No confirmed indications that the night side of Venus is colder than the day side		
Chemical composition of the atmosphere from unmanned spacecraft Venera-4 and Venera-6:		
carbon dioxide CO_2		$97 \pm 4\%$
nitrogen N_2		no more than 2%
water H_2O		0.05%
other gases: CO, O_2, HCl, HF		admixtures

Atmospheric pressure on surface	P	100 ± 40 atm
Altitude of uniform atmosphere:		
at its base	H	13 km
at level of obscuration of Regulus	H	6.8 km
Optical thickness of cloud layer in visible band	τ_0	70 ± 40 /76
Cloud layer has large heterogeneities (partial gaps)		
Maximal electron concentration in the ionosphere at an altitude of about 90 km over the cloud layer, by day (by night it is 50 times smaller)	n_e	$5.5 \cdot 10^5$ cm^{-3}

No magnetic field was detected on Venus (as the dipole is 3000 times weaker than on Earth)

EARTH

Mean distance from Sun	a	1.000 A.U.
Eccentricity of orbit	e	0.017
Rotation period around Sun	P	365.256 days
Mean rate of motion in orbit	v	29.8 km/sec
Equatorial diameter	D_E	12,756.3 km
Polar diameter	D_P	12,713.6 km
Mean diameter	D	12742.1 km
Flattening $\varepsilon = (D_E - D_P):D_E$	ε	1 : 298.2
Area of disk visible from the Sun at an average distance from it	Ω	$0.57 \cdot 10^{-8}$ sterad
Mass in solar masses	$\mathfrak{M}$	1 : 332944
Absolute mass	$\mathfrak{M}$	$5.976 \cdot 10^{27}$ g
Volume	V_0	$1.083 \cdot 10^{27}$ cm^3
Mean density	$\bar{\rho}$	5.517 g/cm^3
Rotation period around axis (stellar days)	P	23 hr. 56 min. 4.099 sec.
Inclination of equator to orbital plane (ecliptic)	i	23°27'

Moment of inertia (in units of $\mathfrak{M}R^2$)	I	0.334
Ratio of centrifugal force to force of gravity at equator	Φ	0.0035
Acceleration of force of gravity at equator	g_E	978.044 cm/sec^2
Critical (parabolic) velocity at which a body leaves the planet	v_e	11.2 km/sec
Stellar magnitude seen from the Sun in the system V		$-3^m.87$
Index of yellowness (excess over color index of Sun) in the system	B-V	$-0^m.6$
Visual spherical albedo	A_v	0.39
Mean temperature over surface of Earth	T_0	285° K
Maximal temperature for the subsolar point	T_{max}	349° K
The Earth radiates into space as an absolute black body with a temperature of	T_{rad}	250° K
Atmosphere of the Earth		
nitrogen	N_2	62,500 cm-atm
oxygen	O_2	16,800 cm-atm
argon	Ar	7440 cm-atm
water	H_2O	from 3000 to 5000 cm-atm
carbon dioxide	CO_2	220 cm-atm
neon	Ne	14 cm-atm
methane	CH_4	1.2 cm-atm
other gases in the form of impurities as a whole less than		2 cm-atm
Atmospheric pressure at sea level	p	1 atm = 1013.25 mbar = 1033.23 G/cm^2
Altitude of uniform atmosphere		8 km
Magnetic field: dipole moment		$8.06 \cdot 10^{25}$ elem. units.
horizontal component	H	0.315 cos ϕ gauss
vertical component	Z	0.630 sin ϕ gauss

(ϕ - geomagnetic latitude)

Mean distance from Sun	a	1.524 A.U.
Eccentricity of orbit	e	0.093
Inclination of orbital plane to ecliptic plane	i	1°51'0"
Rotation period around Sun	P	1.881 years
Synodic rotation period	S	779.9 days
Mean rate of motion in orbit	v	24.1 km/sec
Equatorial diameter	D_E	6,800 km (*)
Polar diameter	D_P	6746 km (*)
Flattening $\varepsilon = (D_E - D_P):D_P$	ε	1 : 125 (*)
Dynamically determined flattening		1 : 190
Angular diameters, seen from Earth during time of mean (by distance) opposition:		
equatorial	d_E	17.9"
polar	d_P	17.76"
Area of disk in mean opposition	ω	$0.6 \cdot 10^{-8}$ sterad
Area of disk visible from Sun at mean distance from it	Ω	$0.7 \cdot 10^{-9}$ sterad
Mass in solar masses	$\mathfrak{M}$	1 : 3111000
Mass in Earth masses	$\mathfrak{M}$	0.1078
Absolute mass	$\mathfrak{M}$	$6.443 \cdot 10^{26}$ g
Volume in Earth volumes	V_0	0.150
Mean density	$\bar{\rho}$	3.97 g/cm^3
Rotation period around axis (stellar days)	P'	24 hr. 37 min. 22.668 sec.
Inclination of equator to orbital plane	i'	23°59'
Moment of inertia (in units of $\mathfrak{M}R^2$)	I	0.389
Ratio of centrifugal force to force of gravity at equator	Φ	0.0043

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(*) The values of D_E and D_P shown here are derived from optical measurements with a maximal error of $\pm$ 20 km. From them the value of the mean diameter $(2\ D_E + D_P);\ 3 = 6769$ km is found to be in good agreement with the mean value of 6758 km derived from radio eclipse by Mariner-4. But the value of flattening computed from them is high, and contradicts the value determined dynamically from the motion of the satellites.

Acceleration of force of gravity at equator	g_e	372 cm/sec^2
The same in units of Earth acceleration	g_e	0.380
Critical (parabolic) velocity at which a body leaves the planet	v_e	5.03 km/sec
Stellar magnitude during time of mean opposition in the system	V	$-2^m.01$
In superior conjunction with the Sun, the planet is weaker by	ΔV	$3^m.41$
Index of yellowness (excess over color index of Sun)		
in system B-V		$+0^m.71$
in system U-I		$+1^m.93$
Visual spherical albedo	A_v	0.16
Thermal spherical albedo	A_b	0.26 ± 0.05
Equilibrium temperature at mean distance from Sun	T_{comp}	216° K
The same for the subsolar point (computed)	T_0	306° K
From measurements in the infrared band, the mean brightness temperature over the disk and the temperature of the subsolar point:	T_b	225° K
at mean distance from Sun		286° K
in perihelion		300° K
in aphelion		273° K
Mean brightness temperature over disk from measurements in microwave region at:		
λ = 0.34 cm	T_b	$190° \pm 40°$ K
3.15 cm		$218° \pm 50°$ K
6 cm		$192° \pm 28°$ K
10 cm		$177° \pm 17°$ K
21 cm		$190° \pm 40°$ K
Chemical composition of atmosphere:		
carbon dioxide	CO_2	75 ± 15 m-atm
carbon monoxide	CO	traces
water: by precipitation from atmosphere a layer is formed with a thickness of	H_2O	35 μ

In the upper atmosphere, as a result of dissociation, atoms of	H, O, C	
Other possible, but unobserved components	N_2, Ar	
Atmospheric pressure on surface	p	20 > p > 6 mbar
Altitude of uniform atmosphere	H	13 km
Ionosphere only on day side with maximal concentration of electrons	n_e	$1.6 \cdot 10^5$ cm^3
Magnetic field	None observed	

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Mars has two satellites, Phobos and Deimos, with a diameter of 15 - 10 km, moving in the equatorial plane of the planet very near it (at distances of 9.37 and 23.52 thousand kilometers), with a period, respectively, of 0.319 and 1.262 days. In mean opposition they appear as objects of 11^m - 12^m.

JUPITER

Mean distance from Sun	a	5.203 A.U.
Eccentricity of orbit	e	0.048
Inclination of orbital plane to plane of ecliptic	i	1°18'17"
Rotation period around Sun	P	11.862 years
Synodic rotation period	S	398.9 days
Mean rate of motion in orbit	v	13.1 km/sec
Equatorial diameter	D_E	141,700 km
Polar diameter	D_P	133,100 km
Flattening $\varepsilon = (D_E - D_P):D_E$	ε	1 : 16.5
Dynamically determined flattening		1 : 15.34
Angular diameter, seen from Earth in mean opposition:		
equatorial	d_E	46.5"
polar	d_P	43.7"
Area of disk seen from Earth in mean opposition	ω	$1.6 \cdot 10^{-8}$ sterad
The same from the Sun at mean distance from it	Ω	$1.04 \cdot 10^{-8}$ sterad

Mass in solar masses	$\mathfrak{M}$	1 : 1047.39
Mass in Earth masses	$\mathfrak{M}$	317.82
Absolute mass	$\mathfrak{M}$	$1.899 \cdot 10^{30}$ g
Volume in Earth volumes	V_0	1347.0
Mean density	$\bar{\rho}$	1.30 g/cm^3
Rotation period of visible surface (cloud layer):		
in the latitudinal limits $\pm$ 12°	P_I	9 hr. 50 min. 30.000 sec.
for the middle latitudes	P_{II}	9 hr. 55 min. 40.632 sec.
Rotation period of decimeter radiation carriers	P_{III}	9 hr 55 min 29.37 sec.
The magnetic axis rotates with the same period relative to the axis of visible rotation; angle between them		10°
Inclination of equator to orbital plane	i'	3°04' /80
Moment of inertia (in units of $\mathfrak{M}R^2$)	I	0.26
Ratio of centrifugal force to force of gravity at equator	Φ	0.084
Acceleration of force of gravity at equator	g_e	2.301 cm/sec^2
The same in units of Earth acceleration	g_e	2.35
Critical (parabolic) velocity at which a body leaves the planet	v_e	57.5 km/sec
Stellar magnitude during time of mean opposition in the system V		$-2^m.55$
In superior conjunction with the Sun, the planet is weaker by	ΔV	$0^m.85$
Index of yellowness (excess over color index of Sun)		
in system B-V		$0^m.20$
in system U-I		$0^m.27$
Visual spherical albedo (λ = 5500 Å)	A_v	0.67
Thermal spherical albedo	A_b	0.45
Equilibrium mean temperature over disk (computed)	T_{comp}	110° K

Actually observed brightness temperature on disk from measurements:		
in infrared band	T_b	126° ± 2° K (1964)
in 8 - 14 μ band	T_b	128° (1963)
in 10 - 14 μ band (color)	T_c	125°
From measurements in the microwave region		
at λ = 0.2 cm the brightness is	T_b	170° ± 80° K
2 cm	T_b	150°
8.6 cm	T_b	149° ± (1967)
21 cm	T_b	400° ?
Over the rotational band, methane molecules λ = 11,070 Å; the rotation temperature	T_{rot}	200° ± 20° K
Chemical composition of the atmosphere above the cloud layer:		180° ± 20° K
molecular hydrogen (spectrally)	H_2	85 ± 15 km-atm
helium (theoretically)	He	26 km-atm
methane (spectrally)	CH_4	100 m-atm
ammonia (spectrally)	NH_3	5 m-atm
Altitude of uniform atmosphere		8 km

Jupiter has 12 satellites of which four (the Galilean satellites) are large celestial bodies comparable in size to the inner planets and the Moon. The others are small with diameters on the order of hundreds of kilometers or less. The nearest, Amalthea, revolves around the planet in 2.5 days, and the remotest, the ninth, in 758 days. Satellites 8, 9, 11, and 12 have a direction of orbital motion, opposite that of Jupiter around its axis and around the Sun.

SATURN

Mean distance from Sun	a	9.539 A.U.	/81
Eccentricity of orbit	e	0.056	
Inclination of orbital plane to plane of ecliptic	t	2°29'22"	

Rotation period around Sun	P	29.458 years
Synodic rotation period	S	378.1 days
Mean rate of motion in orbit	v	9.6 km/sec
Equatorial diameter	D_E	120,670 ± 600 km
Polar diameter	D_P	109,110 ± 600 km
Flattening $\varepsilon = (D_E - D_P) : D_E$	ε	1 : 10.4
Dynamically determined flattening		1 : 10.2
Angular diameter, seen from Earth in mean opposition:		
equatorial	d_E	19.5"
polar	d_P	17.6"
Area of planet's disk seen from Earth in mean opposition	ω	$0.63 \cdot 10^{-8}$ sterad
The same from the Sun at mean distance from it	Ω	$0.51 \cdot 10^{-8}$ sterad
Mass in solar masses	$\mathfrak{M}$	1 : 3500.5
Mass in Earth masses	$\mathfrak{M}$	95.112
Absolute mass	$\mathfrak{M}$	$5.684 \cdot 10^{29}$ g
Volume in Earth volumes	V_0	770.5
Mean density	$\bar{\rho}$	0.71 g/cm^3
Rotation period of surface (cloud layer):		
in latitude range ± 25° - 30°	P_I	10 hr. 14 min.
at other latitudes	P_{II}	10 hr. 40 min.
Inclination of equator toward orbital plane	i'	26°44'
Moment of inertia in units of $\mathfrak{M}R^2$	I	0.21
Ratio of centrifugal force to force of gravity at equator	Φ	0.142
Acceleration of force of gravity at equator	g_e	944 cm/sec^2
The same in units of earth acceleration	g_e	0.965
Critical (parabolic) velocity at which a body leaves the planet	v_e	37 km/sec
Stellar magnitude (with the exception of the brightness of the ring) in mean opposition in the system	V	$+0^m.67$
In superior conjunction with the Sun the planet is weaker by	ΔV	$+0^m.46$

The ring introduces additional brightness which, in stellar magnitudes, is expressed by the terms + 0.44 ϕ - 2.60 sin B + 1.25 $\sin^2 B$, where ϕ is the phase angle, B is the angular elevation of the Earth above the plane of the ring.		
At maximal opening of the ring, that is, when B = 28°, the stellar magnitude of the planet is smaller by	ΔV	$0^m.95$
Yellow index (excess over ΔV by the color index of the Sun) in the system	B-V	$+0^m.41$
Visual spherical albedo	A_v	0.69
Mean equilibrium temperature over disk	T_{comp}	80° K
Brightness temperature from measurements in the infrared band (different authors)	T_b	from 85° to 125° K
From measurements in the microwave region at		
λ = 0.86 cm	T_b	96° ± 20° K
1.53 cm		146° ± 23° K
3.45 cm		106° ± 21° K
6 cm		217° ± 30° K
10 cm		196° ± 44° K
21 cm		303° ± 50° K
Chemical composition of atmosphere above cloud layer:		
molecular hydrogen	H_2	∿ 40 km-atm
methane	CH_4	∿ 350 m-atm
no helium observed	He	undoubtedly exists
ammonia	NH_3	unconfirmed

Rings of Saturn

Ring A, outer, brightness moderate at distance from center of planet Cassini scale	from 138 to 120 thousand km
Ring B, middle, brightest, at distance from center of planet - Dark space	from 116 to 90 thousand km
Ring C, inner, dark (rigid, inner boundary not sharp), at distance from center of planet of	from 89 to 71 thousand km

Thickness of rings	2.8 ± 1.5 km
Hypothetical mass of rings in Saturn masses	$10^{-4} - 10^{-5}$

Saturn has ten satellites of which only one, Titan, possesses planetary dimensions (D = 4950 km) and significant mass ($2.4 \cdot 10^{-4}$ of the planet's mass). The nearest, Janus, (discovered in 1966) moves around the planet at a distance of 157.5 thousand kilometers with a period of 18 hours and its diameter is estimated to be 350 km. The remotest, Phoebe, revolves around the planet for 550 days in the retrograde direction, at a mean distance of 13 million kilometers.

URANUS

Mean distance from Sun	a	19.182 A.U.
Eccentricity of orbit	e	0.047
Inclination of orbital plane to plane of ecliptic	i	0°46'23"
Rotation period	P	84.015 years
Synodic rotation period	S	369.7 days
Mean rate of motion in orbit	v	6.8 km/sec
Equatorial diameter	D_E	49,130 ± 100 km
Polar diameter	D_P	48,200 ± 1000 km
Flattening $\varepsilon + (D_E - D_P) : D_E$	ε	1 : 53
Angular diameter seen from Earth in mean opposition:		
equatorial	d_E	3.73"
polar	d_P	3.66"
Area of disk, seen from Earth in mean opposition	ω	$2.5 \cdot 10^{-10}$ sterad
The same from the Sun at mean distance	Ω	$2.3 \cdot 10^{-10}$ sterad
Mass in solar masses	$\mathfrak{M}$	1 : 22934
Mass in earth masses	$\mathfrak{M}$	14.517
Absolute mass	$\mathfrak{M}$	$8.676 \cdot 10^{28}$ g

Volume in Earth volumes	V_0	55.9
Mean density	$\bar{\rho}$	1.47 g/cm^3
Rotation period around axis (stellar days)	P'	10.8 hours
Inclination of equator to orbital plane	i'	98° (*)
Moment of inertia (in units of $\mathfrak{M}R^2$)	I	0.236
Acceleration of force of gravity at equator	g_e	967 cm/sec^2
The same in units of Earth acceleration	g_e	0.99
Critical (parabolic) velocity at which a body body leaves the planet	v_e	21.6 km/sec
Stellar megnitude during time of mean opposition in the system V		+ 5^m,52
Yellow index (excess over color index of Sun)		
In system B-V		- 0^m, 07
in system U-I		- 1^m, 62
Visual spherical albedo	A_v	0.93 (**)
Mean equilibrium temperature over disk	T_{comp}	60° K
Temperature measured in the infrared region in the range of 17.5 - 25 μ	T_b	55° ± 3° K
Brightness temperature measured in micro-wave region at		
λ = 1.9 cm	T_b	220° ± 35° K
3.75 cm		130° ± 40° K
6 cm		100° ± 35° K
11.3 cm		128° ± 40° K
Rotational temperature in CH_4 absorption band	T_{rot}	63° ± 10° K
The same in the H_2 absorption band	T_{rot}	124 ± 30° K
Chemical composition of atmosphere:		
large amount of hydrogen	H_2	
theoretically large amount of helium	He	

(*) The direction of the axial rotation is retrograde; therefore, we assume i > 90°.

(**) The largest of the planets in the solar system.

abundance of methane	CH_4	from 3 to 150 km-atm, based on various estimates of the thickness of the CH_4 absorption band in the planet's spectrum.
Pressure at the boundary of the cloud layer	p	3 atm

Uranus has five satellites. All of them are small (from 100 to 500 km in diameter). They move practically in circular orbits, lying almost in the planet's equatorial plane with periods from 1.4 to 13.5 days; the direction of motion of the satellites coincides with the direction of Uranus' rotation — that is, it is retrograde.

NEPTUNE

Mean distance from Sun	a	30.057 A.U.
Eccentricity of orbit	e	0.009
Inclination of orbital plane to plane of ecliptic	i	1°46'22"
Rotation period around Sun	P	164.788 years
Synodic rotation period	S	367.5 days
Mean rate of motion in orbit	v	5.4 km/sec.
Diameter from optical measurements	D	47,000 ± 2000 km
Diameter at level of half of loss of brightness of the star during obscuration by Neptune	D'	50,450 ±60 km
Flattening	ε	1 : 48
Dynamically determined compression	ε	1 : 58
Angular diameter, seen from Earth in mean opposition	d	2.24"
Area of planet's disk seen from Earth in mean opposition	ω	$0.93 \cdot 10^{-10}$ sterad
The same from the Sun at mean distance	Ω	$0.86 \cdot 10^{-10}$ sterad
Mass in solar masses	$\mathfrak{M}$	1 : 19340
Mass in Earth masses	$\mathfrak{M}$	17,216

Absolute mass	$\mathfrak{M}$	$1.029 \cdot 10^{29}$ g
Volume in Earth masses	V_0	50.65
Mean density	ρ	1.88 g/cm^3
Rotation period around axis (stellar days)	P'	15.8 hours /85
Inclination of equator to orbital plane	i'	29°
Moment of inertia (in units of $\mathfrak{M}R^2$)	I	0.241
Ratio of centrifugal force at equator to force of gravity	Φ	0.022
Acceleration of force of gravity at equator	g_e	1194 cm/sec^2
Same in units of Earth acceleration	g_e	1.258
Critical (parabolic) velocity at which a body leaves the planet	v_e	25 km/sec
Stellar magnitude during time of mean opposition in system V		$+7^m.84$
Yellow index (excess over color index of Sun)		
in system B-V		$-0^m.15$
in system U-I		$-2^m.02$
Visual spherical albedo	A_v	0.84
Mean equilibrium temperature over disk	T_{comp}	51° K
Mean temperature measured over the disk at a wavelength of λ = 3.12 cm	T_b	115° $\pm$ 36° K
From obscuration of star at level D'	T	110° - 130° K
Significant part of atmosphere composed of:		
hydrogen	H_2	
methane	CH_4	$\sim$ 5 km-atm
helium theoretically	He	
Altitude of uniform atmosphere	H	50 - 60 km

Neptune has two satellites. The nearer, Triton, has planetary dimensions and moves around the planet in a retrograde direction at a distance of 15.85 radii with a period of 5.88 days. The other, Nereid, is very small. It revolves around the planet in a posigrade direction at a distance of 250 of its radii, with a period of 359 days.

Pluto

Mean distance from Sun	$a^{(*)}$	39.750 A.U.	
Eccentricity of orbit	$e^{(*)}$	0.253	
Inclination of orbital plane to plane of ecliptic	$i^{(*)}$	17°8'.5	
Rotation period around Sun	$P^{(*)}$	250.6 years	
Synodic period of rotation	S	366.8 days	
Mean rate of motion in orbit	v	4.7 km/sec	
Diameter	$D^{(**)}$	6000 km	/86
Angular diameter seen from Earth at mean opposition	d	0".23	
Area of planet's disk seen from Earth in mean opposition (practically the same as from the Sun)	ω	$1 \cdot 10^{-12}$ sterad	
Mass in solar masses	(**)	1 : 1,812,000	
Mass in Earth masses	(**)	0.18	
Absolute mass	(**)	$1.08 \cdot 10^{27}$ g	
Volume in Earth volumes	V_0	0.096	
Mean density	$\bar{\rho}$ (**)	10.4 g/cm^3	
Rotation period around axis (stellar days)	P'	6.39 days	
Stellar magnitude during time of mean opposition in system V		+ 14.90	
Yellow index (excess over color index of Sun)			
in system B-V		$+0^m.17$	
in system U-I		$+0^m.17$	
Visual spherical albedo	$A_v^{(**)}$	0.14	
Mean equilibrium temperature over disk	T_{comp}	43° K	

(*) It varies significantly for short periods of time as a result of strong perturbations from other planets.

(**) Very unreliable figure. From the nonoccuring obscuration of the star, located very near the visible path of the planet, the upper limit was determined for the diameter D = 5500 km (but also with a large error) and then $\bar{\rho}$ = 12.4 g/cm^3. However, the mass is not known accurately (from perturbations in the motion of Neptune) and may be two times smaller than the figure given.

Atmosphere	unknown
Satellites	unknown

THE MOON

Mean distance from Earth	a	384,400 km
Eccentricity of orbit	e	0.055
Inclination of orbit to plane of ecliptic	i	5°8'43.4" (*)
Stellar period of rotation	P	27.3217 days(**)
Synodic period of rotation	S	29.5306 days(***)
Mean rate of motion in orbit	v	1.023
Diameter	D	3476.0 km
Diameter in units of Earth equatorial diameter	D'	0.2725
Angular diameter at mean distance from Earth	d	31'5.6"
or		0.00905 rad
Area of disk visible from Earth at mean distance	ω	$6.45 \cdot 10^{-5}$ sterad
Same visible from Sun at mean distance from it	Ω	$0.42 \cdot 10^{-9}$ sterad
Mass in solar masses	$\mathfrak{M}$	1 : 27069400
Mass in Earth masses	$\mathfrak{M}$	1 : 81.3030
Absolute mass	$\mathfrak{M}$	$7.35 \cdot 10^{25}$ g
Volume in Earth volumes	V_0	0.020
Mean density	$\bar{\rho}$	3.35 g/cm^3
Rotation period around axis (stellar days)	P'	27.3217 days
Inclination of equatorial plane to plane of ecliptic	i"	1°33'
Mean inclination of equatorial plane to orbital plane	i'	6°41'

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(*) With respect to the Earth's equator, the inclination of the lunar orbit varies between 23°27' ± 5°9', that is, from 18°18' to 28°36'.

(**) Because of perturbations from the solar side, it varies within limits of of seven hours.

(***) Because of eccentricity of orbit, it varies within limits of 13 hours.

Moment of inertia (in units of R^2)	I	0.39
Acceleration of force of gravity on surface	g	162.0 cm/sec^3
Same in units of Earth acceleration	g	0.166
Critical (parabolic) velocity at which a body leaves the Moon	v_e	2.37 km/sec
Integral brightness at mean half-moon in system V		$-12^m.74$
Yellow index (excess over color index of Sun)		
in system B-V		$+0^m.29$
in system U-I		$+1^m.29$
Visual spherical albedo	A_v	0.067
Temperature of subsolar point	T_{comp}	387° K
From measurements in the infrared band	T_b	371° K (1939)
Rapid cooling during lunar eclipse up to		175° K
Two days after onset of night up to	T'	122° K (1963)
Temperature at midnight at the equator	T_b	115° K
Mean temperature over the entire surface	T_{comp}	274° K
Actually measured brightness temperature in the microwave region range from 185° to 270° with no explicit dependence on wavelength		[Not given]
Amplitude of radio temperature oscillations during lunar days (synodic rotation period) varies from		
from (at λ = 0.13 cm)		120 - 115° K
to (at λ = 10 - 20 cm)		5 - 7° K
and is practically equal to zero at $\lambda > 30$ cm		
Atmosphere on Moon in Earth units no greater than		10^{-12}
Magnetic field on lunar surface		$< 4\gamma$
Magnetic moment		$< 10^{20}$ erg/gauss
or in Earth units		$< 10^{-6}$

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